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Carbon neutrality approaches in buildings and agriculture sectors

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Carbon neutrality approaches in buildings and agriculture sectors

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Editorial: Carbon neutrality approaches in buildings and agriculture sectors

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Editorial on the Research Topic
Carbon neutrality approaches in buildings and agriculture sectors

Climate change is a critical global challenge. Carbon neutrality has become a grand and imperative goal to cope with this challenge (Chen et al., 2022; Yang et al., 2022). In the context of carbon neutrality, green policy, green innovation, green behaviors, and green industrial transformation have triggered increasing research interests (Si et al., 2020; 2022; Zhao et al., 2020; Wang et al., 2021; 2023). It is noteworthy that the building sector consumes more than 40% of global energy and accounts for approximately 40% of global greenhouse gas emissions (He et al., 2020; Wang et al., 2021). The building sector is under particularly high pressures to transform its development paths (Zhang et al., 2022). Therefore, this Research Topic is launched to produce a comprehensive reflection of research on carbon neutrality, especially the research related to the transformation of the building sector. The guest editors aim to highlight avenues for new research by capturing the current state-of-the-art in carbon neutrality research and practice and supporting the foundation for future work. This Research Topic welcomed carbon neutralization studies in the field of economics and management and embraces diverse research methods and article types, including systematic literature review, conceptual framework development, analytical and simulation modeling, quantitative and qualitative empirical studies, and other rigorous research. Twelve papers, including this editorial, were finally included in this Research Topic. In the next section, we briefly describe the contributions of these papers.

The paper can be divided into three levels, including the micro-behavioral level, the meso-industry level (especially in the building sector), and the macro-development level. First, there are three papers rooted in the micro-behavioral level. Wen and Qiang developed a Bayesian network model to address the complexity of stakeholder concerns and optimize the decision-making process in green building projects from the perspective of social sustainability. The feasibility of the Bayesian network model was verified by the case of the Wuhan International Commerce Center. This study facilitates a better accommodation of social sustainability in the decision-making process for green buildings. Liu conducted face-to-face surveys in North China and revealed conflicting perceptions of different stakeholders on the pathways to improve air quality. This study helps to better balance the concerns of different stakeholders in the process of developing air quality improvement policies. Ao et al. conducted a questionnaire survey in areas affected by the natural disaster (i.e., Wenchuan earthquake) to investigate the status of post-disaster reconstruction and the level of satisfaction of residents in these areas. This study contributes to enriching research on residents' satisfaction as well as reconstruction practices after natural disasters.

Second, there are five papers rooted in the meso-industry level. Guo and Li developed a "mi" shaped conceptual framework for the collaborative development of intelligent construction and building industrialization. This framework, which includes the four dimensions of the driving force, resource supply, collaborative operation, and trust guarantee, contributes to clarifying the development directions of intelligent construction and building industrialization. Tang et al. provided a bibliometric analysis of 296 papers on government behaviors in carbon emissions and developed a framework for aligning carbon emissions policies in the building sector. This study revealed the transmission path of government behaviors toward carbon emissions in the building sector and shed light on potential directions for future research. Xia et al. developed an evaluation index system that considers the stability of the tunnel construction process and the level of carbon emission and proposed an intelligent decision method to better assess the utility of excavation schemes. The decision indicator system and method can be applied to the selection of the excavation scheme in engineering projects. Lu and Juan conducted questionnaire surveys to analyze the differences between developers' and users' perceptions of green building technologies and developed an optimal decision-making model taking into account developers' incremental cost and benefit assessment to assist in selecting green building technologies. Li and Lu introduced the green credit guidelines as a quasi-natural experiment and applied PSM-DID to examine the effects of green credit policy on the performance of construction energy-saving firms, with consideration of the mediating role of firms' debt. This study revealed the nuanced effects of green credit policy and provided implications for facilitating the development of energy-saving firms in the context of carbon neutrality.

Third, there are three papers rooted in the macro-development level. Xie selected Chinese-listed firms from the Rankins index between 2009 and 2017 as the sample and examined the effect of corporate social performance on green technology, with consideration of the moderating role of slack resources. This study provided implications for promoting green technology innovations. Khurshid et al. examined the effect of climate change shocks on economic growth using non-linear analysis. This study revealed the asymmetrical effects of CO_2 emissions and mean temperature on economic growth both in the long run and short run and provided macro-level policy suggestions for mitigating climate change. Wang et al. analyzed China's policies related to carbon neutrality and provided suggestions for aligning the carbon policy system.

In summary, the contributed papers focus on topics related to carbon neutrality, climate change, and sustainable development at three levels, including the micro-behavioral level, the meso-industry level, and the macro-development level. The meso-industry level studies are mainly focused on the building sector. There is a huge potential to explore carbon neutrality in the agriculture sector.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Managing Stakeholder Concerns in Green Building Projects With a View Towards Achieving Social Sustainability: A Bayesian-Network Model

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Green building projects (GBPs) involve multiple interdependent stakeholders, whose individual and separate concerns have different degrees of impact on sustainability management. These concerns are highly complex, subject to many uncertainties, and pose significant challenges to decision-makers during sustainability assessments, especially with regard to the social aspects of the project. As such, addressing the complexity of stakeholder concerns and optimizing the decision-making process in green building projects from the stakeholder perspective are crucial to improving practices in social sustainability management. However, to date, there is a lack of relevant empirical studies on this subject. This study proposes a decision-making model based on Bayesian networks (BN); a project network decision model is also constructed from a social sustainability perspective. A diagnostic analysis and sensitivity analysis of the constructed model identify the key stakeholder concerns that affect the social sustainability of the project. To verify its feasibility, the BN model is applied to a green building project, specifically, the Wuhan International Commerce Center, China. The results identify green design and construction, an abundance and stability of project funds, and conveniently-situated service facilities as the primary, sensitive stakeholder concerns that significantly impact social sustainability. The findings show that the BN model can be used as a long-term management decision-making tool for this project. The uncertainty problem associated with changes in sustainability levels induced by the multiplicity of stakeholders is addressed in this study. Furthermore, the findings expand the topic of social sustainability in green construction projects. These findings aid project decision-makers in managing stakeholders individually based on their various concerns, as well as improving the social sustainability of green building projects.

Keywords: green building projects, stakeholder concerns, social sustainability, Bayesian networks, decision-making process

1 INTRODUCTION

The public has become aware of the importance of sustainable building due to the enormous energy consumption and severe environmental impact of the global construction industry. Therefore, the development and construction of green buildings has become a standard solution and practice in many nations (Hwang and Tan 2012). The aim of green building practices is to improve the efficiency of the resource utilization of building projects throughout their whole life cycle. Green buildings also decrease environmental pollution, improve the human living environment, and ultimately promote the sustainable development of society (Darko et al., 2019). The complexity of green building projects (GBPs) is often manifested in rigorous technical evaluation indicators, the engagement of numerous stakeholders, many uncertain risks, and high-level sustainability goals (Zhao et al., 2016; Mok et al., 2018; Bohari et al., 2020). Although many studies have focused on the interrelationship between GBP stakeholders (Doloi 2013; Seuring and Gold 2013; Yang and Shen 2015; Li et al., 2018a), discovering how to face the challenges posed by the complex interrelationships among stakeholders in construction projects remains difficult (Lin et al., 2019; Yang et al., 2020). This is because these previous studies have mostly separated social sustainability from stakeholders. Adopting such a fragmented strategy undermines the synergistic effect of the complexity of interacting stakeholder concerns (drivers), as well as having a negative impact on sustainability.

In fact, achieving the social sustainability objectives related to green building requires the consideration of more human activities; project success also depends more on the participation of stakeholders (Mok et al., 2017a). Moreover, studies have shown that different stakeholder concerns (and the complex interactions) create many obstacles to a project's success, which in turn increases the difficulty of managing stakeholders (Control et al., 2008; Hwang and Ng 2013; Li et al., 2016; Luo et al., 2017). Additionally, the increasing demand for sustainable knowledge and technology renders the managing of stakeholders even more challenging (Schröpfer et al., 2017). These challenges affect the realization of social sustainability objectives. Project decision-makers, therefore, need to coordinate this interrelationship according to different stakeholder concerns and appropriately arrange stakeholder participation that follows the whole project's life cycle. Although stakeholder management is generally adopted in existing GBP management literature (Qiang et al., 2021), as it presents a systematic approach to sustainability assessments, the interdependency between social sustainability and stakeholder concern complexity has not been reflected in the existing framework.

Although extensive research has focused on sustainability assessment indicators, so far, no general consensus has been reached on social sustainability indicators for GBPs (Chen et al., 2015; Al-Jebouri et al., 2017; Goel et al., 2020). These studies have addressed various topics, such as megaproject social responsibility (Lin H. et al., 2017), stakeholder engagement with regard to achieving sustainability (Bal et al., 2013), a lifecycle-based sustainability indicator framework (Chong et al., 2016), and successful delivery of GBPs (Olanipekun et al., 2017). Social sustainability evaluation indicators can effectively identify the social sustainability level of GBPs; these indicators are powerful decision-supporting tools that foster sustainable development (Zhong and Wu 2015; Chong et al., 2016; Olanipekun et al., 2017; Yadegaridehkordi et al., 2020). For green buildings to be socially sustainable, they must abide by relatively strict evaluation standards. The complexity of the project also often results in differences between the practiced decision-making and the ultimate goal (San Cristóbal et al., 2018). Multitudinous sustainable evaluation indicators and stakeholder concerns are available. The connections between them are sophisticated and often change when they are integrated, thus further aggravating the decision-making problems. However, the existing stakeholder management body of knowledge in terms of traditional assessment methodologies and network analysis, on the other hand, is insufficient and cannot provide effective solutions to the aforementioned problems. To address this issue, this research proposes a new method for answering the following research questions (RQ):

RQ1: In existing literature, how is the interdependency between stakeholder concern complexity and social sustainability, in particular, treated?
RQ2: How can a decision-making model be developed that prioritizes stakeholder concerns while also facilitating GBPs sustainability management practices?
RQ3: In GBPs, how are stakeholder concern complexity and social sustainability interdependent?

The Bayesian network (BN) is widely used in decision-making research, given BN's superiority when dealing with complex uncertain relations and with capturing interdependency between distinct concepts (represented by stakeholders and sustainability in this paper) (Castillo et al., 2016; Bakshan et al., 2017; Chen et al., 2019). In addition, the use of BN statistics data for sustainable decision-making offers confirmed advantages over traditional optimization approaches (Mkrtchyan et al., 2016; Sierra et al., 2018). Within the theoretically-grounded BN framework, this paper aims to propose a new process, namely "stakeholder concern and sustainability management (SCSM)". This approach integrates all stages of the decision-making process and the consequences affecting the GBP's sustainability objectives. A BN model that represents the relationships among stakeholder concerns and social sustainability objectives is constructed in this study. In this model, the stakeholder concern complexity attributes are represented as deterministic nodes; social sustainability indicators are represented as chance nodes. Through a diagnostic analysis and a sensitivity analysis of this constructed model, key stakeholder concerns that affect the social sustainability of the project can be identified. To verify its feasibility, the BN model is applied to a specific GBP, namely the Wuhan International Commerce Center, China. The decision-making model is used to individually manage stakeholders, according to their different concerns. By optimizing sustainable decisions through the developed model, decision-makers can improve the social sustainability of GBPs. Using a systematic review method, this paper identifies current research gaps and sustainability needs in the construction industry and presents findings from 13 semi-structured interviews conducted with green building sector experts from China. New insights into future developments are also provided, as well as the potential for future research in the field.

This study is structured as follows: In **Section 2**, the theoretical foundation of stakeholder concern and Bayesian networks are introduced. In **Section 3**, a Bayesian network analysis method is developed. In **Section 4**, the SCSM model is established and verified through a case study. In **Section 5**, the obtained results are discussed. Finally, the conclusion, including the main contributions, potential future work, and limitations are presented in **Section 6**.

2 LITERATURE REVIEW AND THEORETICAL UNDERPINNING

2.1 The Concepts of Stakeholder and Stakeholder Concerns in Green Building Projects

The concept of "stakeholder concern complexity" is grounded in stakeholder theory. Quite a few papers have, in fact, investigated GBP complexity from the perspective of stakeholders by analyzing the stakeholders' roles, interactions, and impacts on project success. Project stakeholders can be both individuals and organizations that are involved in a project, or who have influenced the project as a result of project implementation (Institute 2009). In a GBP, the relationships between stakeholders are more complex than in typical projects, due to the fact that increased project complexity creates various interests and conflicts (Yang and Zou 2014; Yang et al., 2016; He et al., 2020). Considering the complexity of the various interactions from a network perspective is a reasonable choice and has been widely applied in existing research. Topics that have been addressed from this perspective include stakeholder engagement networks (Mok et al., 2015; Mok and Shen 2016; Burga and Rezania 2017), stakeholder collaboration networks (Cao et al., 2016; Tang et al., 2018; Li et al., 2019), stakeholder-related risk networks (Yang and Zou 2014; Castillo et al., 2016; Yang et al., 2016), stakeholder-related indicator networks (Wu et al., 2018), and stakeholder concern networks (Mok et al., 2017b, 2018). Journeault et al. (2021) pointed out that five critical roles of stakeholders, namely those of the trainer, analyst, coordinator, specialist, and financial provider, should be focused upon by the government, as these roles contribute significantly to overcoming different barriers to the integration of sustainability practices. These studies particularly emphasize the significance of stakeholder engagement for green practices; they also clarify the undeniable responsibility of stakeholders to foster a more sustainable construction environment. Decision-makers face the challenge of identifying and filtering the key stakeholders from all the project participants. Thus, stakeholder analysis is a vital process for the decision-makers when addressing this issue (Li et al., 2012).

According to the definition and characteristics of the stakeholder as presented above, stakeholder concerns in this study refer to interests that are closely related to stakeholders, and which have a certain probability to change during the implementation of the project (Olander and Landin 2005). In previous studies, different classifications of stakeholder concerns were applied, such as social, cost, legal, organizational, technological, environmental, procurement, and ethical (Mok et al., 2017b); economic, environmental, social, and ethical (Mok et al., 2018), and social, economic, safety, equity, responsibility, and ethical (Lin X. et al., 2017; Sperry and Jetter 2019). Project failure is generally the result of decision-makers not being able to address the diversity of stakeholder concerns, which in turn leads to an inability among project stakeholders to achieve a unified sustainable goal (He et al., 2020). Therefore, conflicts of interest must necessarily be reduced. This can be done by optimizing decision-making and coordinating the complex interactions between stakeholder concerns (Toor and Ogunlana 2010).

The complexity of stakeholder concerns further aggravates the complexity of GBPs and imposes challenges on project sustainability decision-making. Although some sustainability studies have used a stakeholder analysis perspective, it appears that the analysis is mostly related to stakeholder relationships, rather than a comprehensive assessment of the stakeholder concerns related to social sustainability objectives. In addition, only a limited number of studies have been conducted in the context of GBPs. Current social sustainability studies lack the integration of empirical and rationalistic angles that could be used to assess causality between stakeholder concern and social sustainability in GBPs. Bridging this gap would enhance the understanding of stakeholder management and improve the sustainability outcomes of GBPs.

In this study, the major stakeholder concerns were identified by integrating previous research with GBP implementation practices. The initial stakeholder concerns are summarized in **Table 1**. This list of concerns does not include all concerns related to GBPs. Instead, the included concerns only relate to social sustainability, and the concerns are developed to build relationships with sustainability indicators, in order to optimize project decisions.

2.2 Social Sustainability in Green Building Projects

Consideration of social sustainability during the construction project life cycle has been strongly encouraged, ever since the Brundtland Report (WCED 1987). Although numerous scholars have attempted to precisely define social sustainability, it is a concept in chaos (Zhang and Mohandes 2020). To achieve consensus, context-specific conception should be adopted in GBPs. The concept of social sustainability refers to the process of constructing a structure that meets the GBP stakeholders' needs throughout the building's life (Almahmoud and Doloi 2015). Landorf (2011) proposed that stakeholders, such as users and neighborhood communities, are centric in terms of social sustainability management, particularly because their diverse needs are the foundation of social

TABLE 1 | Stakeholder concerns associated with GBPs.

Concern code	Stakeholder concern	References
C1	Changing needs of the project	Li et al. (2012); Mok et al. (2018); Sperry and Jetter (2019); Paper (2020)
C2	Job opportunities created by the project	Mok et al. (2018); Goel et al. (2020); Vuorinen and Martinsuo (2019); Li et al. (2012)
C3	Economic benefits of the project	Mok et al. (2018); Xue et al. (2020); Li et al. (2012); Paper (2020)
C4	Stable development of the local economy	Mok et al. (2018); Li et al. (2012); Xue et al. (2020); Lam et al. (2019)
C5	Practicality of the project design	Mok et al. (2018); Goel et al. (2020); Li et al. (2012); Lam et al. (2019); Wu et al. (2016)
C6	Developed transportation network	Mok et al. (2018); Goel et al. (2020); Li et al. (2012); Vuorinen and Martinsuo (2019)
C7	Conveniently surrounding service facilities	Goel et al. (2020); Li et al. (2012); Vuorinen and Martinsuo (2019); Xue et al. (2020)
C8	Green design and construction	Bohari et al. (2020); Mok et al. (2017b); Li et al. (2012); Su et al. (2020); Weerasinghe and Ramachandra (2020)
C9	Reduction of environmental pollution	Xue et al. (2020); Li et al. (2012); Lam et al. (2019); Li et al. (2016); Winston (2021)
C10	Aesthetic design of the building	Mok et al. (2017b); Li et al. (2012); Lam et al. (2019); Wu et al. (2016)
C11	Harmony between project and environment	Bohari et al. (2020); Li et al. (2012); Lam et al. (2019); Weerasinghe and Ramachandra (2020)
C12	Unique local characteristics	Lam et al. (2019); Li et al. (2012); Vuorinen and Martinsuo (2019)
C13	Conservation of local historical heritage	Li et al. (2012); Lam et al. (2019); Dansoh et al. (2020)
C14	Approval process and project policies	Su et al. (2020); Xue et al. (2020); Li et al. (2016)
C15	Qualified green building technology	Bohari et al. (2020); Goel et al. (2020); Li et al. (2016)
C16	Project team's green building project experience	Bohari et al. (2020); Xue et al. (2020)
C17	Safety at the construction site	Francisco de Oliveira and Rabechini (2019); Sperry and Jetter (2019); Lam et al. (2019)
C18	Project's design flexibility	Mok et al. (2017a); Li et al. (2016); Xue et al. (2020)
C19	Project's design changes	Bohari et al. (2020); Xue et al. (2020); Winston (2021)
C20	Abundance and stability of project funds	Goel et al. (2020); He et al. (2020); Xue et al. (2020)
C21	Effective decision-making of the project team	Mok et al. (2018); Bohari et al. (2020); Vuorinen and Martinsuo (2019)
C22	Contractors' and consultants' attitudes toward green building design	Mok et al. (2018); Bohari et al. (2020); Li et al. (2016); Weerasinghe and Ramachandra (2020)
C23	Mutual trust and understanding among stakeholders	Dansoh et al. (2020); Francisco de Oliveira and Rabechini (2019); Keeys and Huemann (2017)
C24	Clear design instructions	Goel et al. (2020); Bohari et al. (2020); Vuorinen and Martinsuo (2019)
C25	Effective communication between the project team and end-users	Xue et al. (2020); Bohari et al. (2020); Keeys and Huemann (2017)
C26	Achievement of project sustainability goals	Goel et al. (2020); Su et al. (2020); Keeys and Huemann (2017)

sustainability. According to Landorf (2011), user comfort, health and safety, and access to services are common concerns of pertinent stakeholders, including the client, end-users, and local authorities. Therefore, in GBPs, social sustainability is closely related to the involvement of stakeholders and largely depends on the stakeholders' concerns.

To assess the social sustainability efficacy, several evaluations, frameworks and models have been developed by scholars over the past two decades (Zuo et al., 2012; Valdes-Vasquez and Klotz 2013; Almahmoud and Doloi 2015). Fernández-Sánchez and Rodríguez-López (2010) selected the ISO-21929 standard as the indicator framework. That study created a methodology identifying sustainability indicators with the technology used in risk management, and categorized social sustainability indicators into six subcategories: culture, accessibility, participation, security, public utility, and social integration. Heravi et al. (2015) compared the importance of seven categories of social indicators in the three phases of construction, operation and maintenance, and demolition. The study proposed that infrastructure improvement and health and safety are the most important social sustainability indicators for the construction phase and operation phase, respectively. Olakitan Atanda (2019) developed a social sustainability assessment framework by adopting Delphi techniques and interviews. The study found that participation and control, environmental education and social equity were the three highest weights in the 35 sustainability indicators of eight categories. Akhanova et al. (2020) employed the stepwise weight assessment ratio analysis (SWARA) to calculate the weights of sustainability indicators in Kazakhstan. The study showed that indoor environmental quality and the quality of building planning solutions are the highest priorities for sustainable construction.

Although social sustainability has also been reported as an important aspect of GBPs, it is typically found to be paid less attention, due to a lack of analytical and theoretical underpinning (Siew et al., 2019; Zang et al., 2022). There appears to be a lack of guidelines that can be used when measuring uncertainties arising from changing stakeholder concerns. Akhanova et al. (2020) showed that the interaction of stakeholder involvement necessarily changes throughout a project life cycle, in order to adapt to the complexities and uncertainties imposed by multifaceted sustainability outcomes. Nevertheless, there is a lack of research into the interactions between social sustainability and stakeholder concern complexity. To visualize the casual relationship between the two, and to develop a decision-making model for sustainability-related objectives, a BN graph is used in this study.

2.3 Limitations of Existing Interdependency Models on Stakeholder Concern and Sustainability Management in Green Building Projects

Researchers have been using different techniques for capturing interdependency between stakeholder engagement and project sustainability, including Analytical Network Process (ANP) (Kiani Mavi and Standing 2018); social network analysis (SNA) (Wu et al., 2021b; Wang et al., 2021)and structural equation modelling (SEM) (Teng et al., 2019; González-Rodríguez and Tussyadiah 2021). Although the ANP can take the complex interdependence at different levels into account, there is still limitations in exploring the behavioral causality of interrelated non-human objects (Zhao et al., 2017). The main criticism of SNA is its inability to address more uncertainty issues and update beliefs upon receiving new interaction relationships (Lee et al., 2018). SEM has its limitation in guaranteeing complex cause-effect relationship when necessary causal conditions cannot be met (Khan et al., 2019).

Existing research on GBPs have mainly focused on environmental and technological aspects like design optimization, GB techniques and energy efficient measures whereas to the best of the authors' knowledge, an integrated stakeholder concern and social sustainability model has not been presented (Chen et al., 2021a; Wu et al., 2021a; Wu et al., 2021b). Green building projects involve complex and intertwined concerns among stakeholders (Wang et al., 2021), the mentioned techniques fail to assess social sustainability within a probabilistic setting of interacting concerns. Furthermore, optimal sustainability strategies cannot be made when adding new concerns to the interdependency models during the life cycle of the GBPs.

To fill this gap, a SCSM model is proposed in this study, which grounded in the theoretical framework of BN. As BN has been one of the most efficient methods to manifest the causal map of complex relationship between interconnected variables (Koseoglu Balta et al., 2021). In addition, there are a number of uncertainties between stakeholders in GBPs, BN presents a well-established tool to cope with these uncertainties (Kumar and Banerji 2022).

2.4 Bayesian Networks Applied to Decision-Making

A BN is a directed acyclic graph composed of nodes and connections (**Figure 1**), the BN's formation combines graph theory and probability theory. Rooted in these theories, BN interprets project sustainability by analyzing stakeholder concern complexity, diagnosing how various stakeholder behaviors can affect social sustainability, recognizing key stakeholder concerns, and identifying opportunities to improve stakeholder management. The nodes of the network represent uncertain variables, their edges represent influential links between variables (Neil et al., 2000). A BN offers advantages in terms of the decision-making related to complex and uncertain problems. As such, BNs have been widely employed in construction projects and the environmental domain. Specifically, Bakshan et al. (2017) used a BN to establish behavioral causality models that improve waste management in buildings. Zhang et al. (2020) used the BN method to analyze the load data of the pile foundation, in order to calculate the design resistance coefficient. Many studies have also addressed dynamic Bayesian networks (DBN). For example, Wu et al. (2015) used a DBN model to provide security solutions based on the dynamics of tunnel road surface damage. Špačková and Straub (2013) established a DBN model to evaluate tunnel construction performance, and Kosgodagan-Dalla Torre et al. (2017) applied a DBN to overcome the obstacles of asset network degradation modeling under conditions of limited data availability.

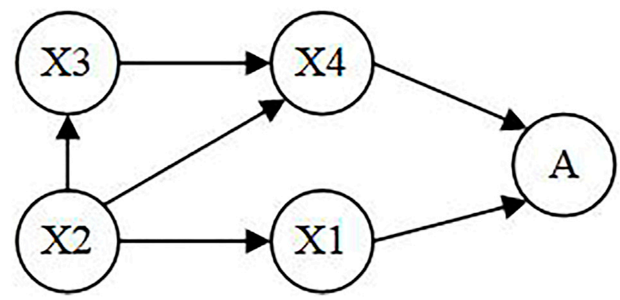

FIGURE 1 | BN topology.

In addition, BNs are widely used for risk prediction. Nepal and Yadav (2015) combined a BN with specific characteristics of reliability engineering to quantify the risk factors that cause related failures. Mkrtchyan et al. (2016) analyzed human reliability risks by establishing a Bayesian trust network. Chen et al. (2019) showed that a combination of the Cloud model and BN can better reflect a real risk situation than classical fuzzy set theory. Through BN, Sanchez et al. (2020) established a project management maturity model that can effectively prevent project cost overruns. Wei et al. (2020) considered the sequence of risks in a smart city and used BNs to model flow risks. Koseoglu Balta et al. (2021) predicted and mitigated delay risk in TBM tunnel projects.

Due to the dynamic changes of the social environment, the interactions between actors have become more complex. To resolve the associated problems, "building blocks" need to be combined, in order to form larger BNs (Neil et al., 2000). Xing et al. (2010) developed dynamic tomography methods to analyze time-evolving networks. Fang et al. (2020) simulated a Zachary network to compare two Bayesian learning strategies. Chen et al. (2021b) developed Bayesian Monte Carlo simulation–driven risk inference method to address schedule issues in infrastructure projects. The study found that Bayesian social learning is more likely to cause asymptotic learning. These researches show the methodological viability of BN analysis in exploring the behavioral causality of interrelated non-human objects. They also provide insights into the network analyzing process in construction projects. It can be concluded that sustainable development is valued. Therefore, it is necessary to identify the factors that affect the social sustainability of GBPs through BN and then make optimal decisions (Sierra et al., 2018). Despite the achievements of previous studies of BNs, factors such as project complexity and stakeholder influence have rarely been addressed (Qazi et al., 2016; Yu et al., 2019), thereby presenting a need to conduct relevant research.

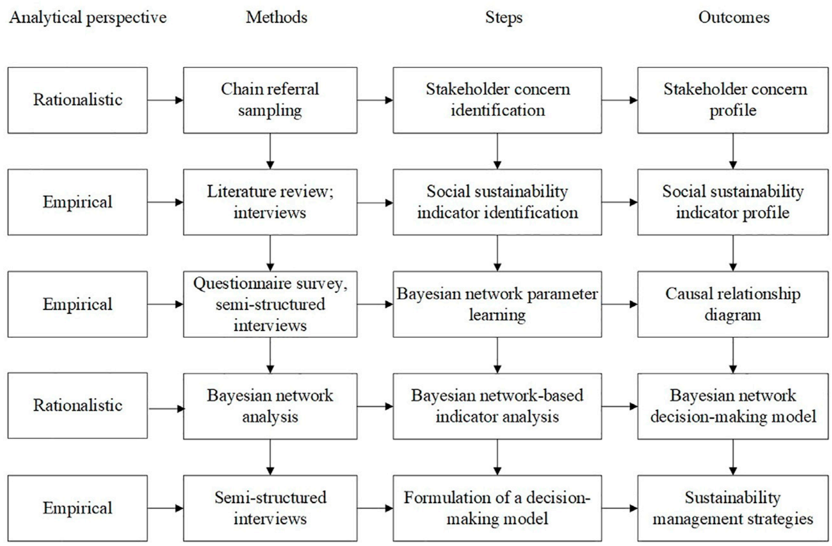

FIGURE 2 | SCSM implementing framework using BN.

3 STAKEHOLDER CONCERN AND SUSTAINABILITY MANAGEMENT MODELING APPROACH

This study proposes a SCSM model approach to analyze the social sustainability changes of the project, which in turn have been caused by various complex stakeholder concerns. To achieve this goal, a literature review, questionnaire survey, BN analysis and semi-structured interviews are applied. Below, **Figure 2** shows the SCSM implementing framework of the present study. The framework is structured in four stages: 1) stakeholder concern and sustainability indicator identification, 2) BN parameter learning, 3) Bayesian network-based indicator analysis, and 4) decision making through the optimization of GBPs from the social sustainability viewpoint.

3.1 Stakeholder Concern and Sustainability Indicator Identification (Stage 1)

Social sustainability has been widely explored in existing literature. However, no consensus has been reached with regard to the social sustainability indicators of green buildings (Goel et al., 2020). Therefore, it is necessary to identify key sustainability indicators that can be used to assess the social sustainability level of green buildings during the buildings' life cycle. In practice, GBPs are complex where sustainable technology is concerned. Also, identifying all stakeholder concerns during the project life cycle is very difficult, due to numerous stakeholder concerns. Thus, this paper mainly focuses on the identification of key stakeholder concerns from the aspect of society, in order to facilitate the establishment of links with social sustainability indicators.

To identify social sustainability indicators, a literature review, questionnaires, and semi-structured interviews were used in this study. In line with the classification of sustainability indicators in existing literature, the social sustainability indicators were generalized, and initial indicator lists were formed. Next, experts who have participated in or are currently participating in GBPs and who are well-known scholars in the field were selected. The experts were selected from representative stakeholder groups, including the government, main contractors, designers, developers, consultants, and research institutions. They were invited to semi-structured interviews, to complete the social sustainability indicator frame. At the same time, experts were invited to rate the social sustainability indicators according to a 5-point Likert scale. These methods were also used to identify stakeholder concerns.

After reaching a consensus on social sustainability indicators and identifying stakeholder concerns, this paper has established causal relationships between the nodes of the BN through the following steps:

Step 1: According to the social sustainability of green buildings, the respective importance of each social sustainability indicator can be assessed.

Step 2: According to each social sustainability indicator, the importance and applicability of the GBP stakeholders' concerns can be assessed.

Step 3: According to each social sustainability indicator and stakeholder concern, the interdependency between them can be assessed.

3.2 Bayesian Network Parameter Learning (Stage 2)

After identifying nodes and determining the causal relationship between them *via* expert interviews, the network structure was constructed. Then, the network parameters could be identified from the training data set, in order to obtain the conditional probability distribution (CPD) of each node. If the network structure is known and the data is complete, maximum likelihood estimation (MLE) and Bayesian maximum a posteriori probability (MAP) are the most common methods used for parameter estimation.

The MLE assesses the degree of fit between the sample and the model based on the likelihood of the sample and the parameter. The form of the likelihood function is shown as **Eq. 1**:

$$L(\theta, X) = p(X|\theta) = \prod_i p(x_i|\theta) \quad (1)$$

where $X = \{x_1, x_2, \ldots, x_n\}$, x represents specific data, and θ represents the model parameters.

If the distribution function of the variable is known, the maximum likelihood value can be obtained by using the Lagrange multiplier method of the above formula, thereby obtaining an estimate of the parameter. This paper used MLE, due to the advantages that method offers, such as consistency, asymptotic efficiency, and representative invariant.

However, in actual investigations, missing data is inevitable. Different situations cause separate mechanisms of data to be missing. The expectation-maximization (EM) method is a common iterative method (based on MLE) that can be applied in cases of missing data. Compared with the traditional missing data repair method, the EM method is based on a rigorous theoretical basis and proof of convergence. The entire EM algorithm is a repeated iteration of the step expectation (E) and step maximization (M). The iteration process can be described as follows:

Assuming that the missing data satisfy the missing at random (MAR) hypothesis, the likelihood function of parameter θ (concerning the observed part of the data) can be expressed as **Eq. 2**.

$$L_0(\theta|X_0) \propto \int p(X_0, X_m|\theta) dX_m \quad (2)$$

where X_0 represents observed data, and X_m represents missing data.

Because this integral exists, maximizing L_0 is quite difficult. The idea of EM is to maximize the expected value of the log-likelihood function of the complete data, thus maximizing L_0. The algorithm first initializes parameter θ_0, then, at the k-th step, the iterations of the E step and the M step are:

1) Replace missing values with estimated (or expected) values (step E):

$$Q(\theta|\theta_k) = \int L(\theta|X_0, X_m) p(X_m|X_0, \theta_k) dX_m \quad (3)$$

2) Identify the parameter θ_{k+1} that maximizes $Q(.|.)$ Q.) (step M):

$$Q(\theta_{k+1}|\theta_k) \geq Q(\theta_k|\theta_{k-1}),\ k = 1, \ldots, n \quad (4)$$

3) Use these new parameters to re-estimate missing values (step E).
4) Re-estimate the parameters (step M), and iterate until convergence. Steps E and M are repeated until the preset parameter convergence condition $|\theta_{k+1} - \theta_k| < \varepsilon$ is met. If ε can be set manually, a small number will generally be obtained.

In BN parameter learning, parameter θ can be set as the conditional probability table (CPT) of the BN, the hidden nodes of the network are regarded as missing data. The goal of step M is to identify the CPT parameter that maximizes the scoring function.

3.3 Bayesian Network-Based Indicator Analysis (Stage 3)

1) Diagnostic analysis. The forms of inference of conditional probability in BNs mainly include causal inference, diagnostic inference, and supporting inference. The main application of this paper uses diagnostic inference, which is also referred to as "reverse inference". The bottom-up reverse inference is an application of inference from the result of the reason. The posterior probability distribution of each indicator is calculated *via* diagnostic analysis, when the sustainability criterion is reached. Then, the factors that affect the achievement of the project's sustainable goals can be identified in time. Project decision-makers can also identify relevant stakeholder concerns, thus optimizing their decision-making. If the stakeholder concern is X_i, its posterior probability distribution can be expressed as $P(X_i = x_i|S = s)$, and can be calculated using **Eq. 5**.

$$P(X_i = x_i|S = s) = \frac{P(X_i = x_i) \times (S = s|X_i = x_i)}{P(S = s)},\quad i = 1, 2, \ldots, N \quad (5)$$

where s represents the state of event S, reached by the sustainability index with P states, x_i represents the state of stakeholder concern X_i with Q_i states. In general, if the value of $P(X_i = x_i|S = s)$ is close to 1, this indicates that X_i is more likely to directly affect the realization of the sustainability index S.

2) Sensitivity analysis. A sensitivity analysis can calculate the degree of influence each variable exerts on other variables, i.e., the procedure can be used to analyze stakeholder concerns that are sensitive to changes in social sustainability indicators. A sensitivity analysis can accurately determine the contributions of different stakeholder concerns to the occurrence of social sustainability indicators. In general, a sensitivity analysis can identify changes in the probability of network node status by changing the configuration parameters of the node. This paper uses the sensitivity performance measure (SPM) to measure the contribution of each stakeholder concern X_i to the sustainability indicator S (Wu et al., 2015). Project decision-makers can propose corresponding measures to increase the social sustainability level, based on these key stakeholder concerns. The $SPM(X_i)$ of each node (representing a

stakeholder concern) can then be calculated using **Eq. 6**. As an example, X_i represents the performance of the stakeholder concerns in the q_i ($X_i = x_i^{q_i}$) state on sustainability index S. In light of actual observations of events (i.e., known evidence), e.g., if X_i is found to be in a state of q_i ($X_i = x_i^{q_i}$), then, $SPM(X_i)$ can be calculated by **Eq. 6**.

$$SPM(X_i) = \frac{1}{Q_i}\sum_{j=1}^{Q_i}\left|\frac{P\left(S = s|X_i = x_i^j\right) - P(S = s)}{P(S = s)}\right|, \quad i = 1, 2, \ldots, N \tag{6}$$

$$SPM(X_i) = \frac{1}{Q_i - 1}\sum_{j=1}^{1,\ldots,q_i-1,q_i+1,\ldots,Q_i}\left|\frac{P\left(S = s|X_i = x_i^j\right) - P\left(S = s|X_i = x_i^{q_i}\right)}{P\left(S = s|X_i = x_i^{q_i}\right)}\right|, \quad i = 1, 2, \ldots, N$$

where s represents the state of event S, reached by the sustainability index with P states, x_i represents the state of stakeholder concerns X_i with Q_i states, and x_i^j represents the j th state of the stakeholder concerns X_i. In general, if the value of $SPM(X_i)$ is close to 1, this indicates that X_i is more sensitive to sustainability index S, if the social sustainability goal is met.

3.4 Decision Making Based on BN (Stage 4)

After the completion of the third stage, the results of BN analysis can be applied to decision-making, in order to address social sustainability issues. Stakeholder concerns that are sensitive to (and have a direct impact on) social sustainability can be identified. Then, relevant stakeholder concerns can be implemented, according to the specific factors that affect the realization of the social sustainability goals of the GBP, effectively enabling reasonable decision-making. In addition, according to the stakeholder concern, the model can be reversed to relevant stakeholders, and the sustainable goals of the project can be implemented in a targeted manner. Similarly, these sustainable management measures provide feedback and thus enable optimization of a BN model that has previously been established.

4 CASE STUDY

This research has adopted a case study approach to explore the interactions between stakeholder concerns and the social sustainability of a unique GBP. The emphasis here is more on "how" and "why", rather than "what". The case study is considered applicable when the study contains various relationships/factors whose interactions are the research focus, and when "how" and "why" questions are considered (Phelan 2011). Furthermore, the collection of the data that are required to identify stakeholder concerns requires several interactions with project stakeholders, in order to generate context-dependent knowledge and minimum intervention on the part of the investigator. As such, using case study methods would be suitable.

Case selection is a rigorous process and should fulfill three criteria. Firstly, a wide range of stakeholders should be involved, as these are the sources of stakeholder concerns. Secondly, major GBPs should be considered, as they usually involve many stakeholders, thereby making the stakeholder concern analysis more meaningful. Lastly, ongoing GBPs should be chosen, as comprehensive information can then be collected. The selected case meets these criteria, and more details are described in the following section.

FIGURE 3 | Front drawing of the WHICC in China.

4.1 Background

As the first green building research pilot city in China, Wuhan occupies a pivotal position in the development of green buildings. Wuhan has made exploratory efforts in green building design, construction, and promotion. The number of GBPs that have been approved by the national three-star certification department is among the highest in China. Wuhan's green building development is representative of Central China. Thus, this paper selected GBPs in Wuhan as a database.

The Wuhan International Commerce Center (WHICC) is a landmark building on Yangtze River Avenue in Wuhan. The front drawing of the WHICC is illustrated in **Figure 3**. At the project design stage, the concept of "green development, circular development, and low-carbon development" was fully implemented, some state-of-the-art sustainable technologies were also adopted. The total project investment is $257.7 million, including two 230-m-high twin towers that integrate business, life, commerce, culture, ecology, and leisure. These two buildings have a construction area of approximately 209,000 m^2 and have obtained LEED gold certification from the United States, as well as three-star certification for green buildings in China. Therefore, this project was selected as a representative case study.

4.2 Data Collection

Preparation of the BN model requires four elements, namely: 1) key stakeholder concerns and social sustainability indicators, 2) the decision variables and the possible states that characterize a GBP, 3) the causality of the decision variables, and 4) CPT for each relation in the network. To obtain these sorts of data, a literature review, semi-structured interviews, and a questionnaire survey were conducted in this study. Firstly, a literature review was adopted to construct the preliminary list of 26 stakeholder concerns and 20 sustainability indicators. Secondly, semi-structured interviews were conducted, in order to identify key stakeholder concerns, social sustainability indicators, decision variables, and causality presented in the form of a matrix. After experts had identified the preliminary list, according to their experience and the practical conditions of the WHICC project, several of the concerns and indicators were removed, since they were duplicated with other indicators and imposed little impact on the social sustainability of the project. For example, stakeholder concern "Reduction of environmental pollution" is more related to environmental sustainability. Ultimately, 12 key stakeholder concerns and 15 social sustainability indicators (selected by at least seven respondents) were identified (Qazi et al., 2016). Although the responses varied in relation to past experiences and general understanding of respondents, we could find some common themes emerging from the matrices. Lastly, a questionnaire survey was used as training samples to obtain the BN parameters using the MLE algorithm, in order to construct a CPT.

The semi-structured interview was conducted between July and October 2019. Due to the inherent difficulty of interviewing all stakeholders, this study selected and interviewed representative stakeholder groups, including the government, main contractors, designers, developers, consultants, and research institutions (Yu et al., 2019). To assure data representativeness, all interviewed and surveyed stakeholders were at senior management level or had 10+ years' work experience in sustainable or green construction-related industries or in relevant disciplines (Li et al., 2018b). In addition, all experts were directly involved in the development, with in-depth knowledge of stakeholder issues throughout the project. According to the guidelines of Mok et al. (2018), the number of experts should between eight and 20 when applying semi-structured interviews. Based on work experience and expertise in the WHICC project, 13 experts were identified, this is the same number as in the research of Qazi et al. (2016). **Table 2** shows the interviewees' detailed information. Furthermore, two main principles were applied when selecting these experts. First, they are all stakeholders involved in the WHICC project. Second, they have rich experience in green building management and decision-making (Zhuang et al., 2019). To ensure the reliability and objectiveness of the collected data, a neutral relationship was maintained with all interviewees. The interviews were audiotaped with the permission of the respondents, in order to obviate any misrepresentation. After the completion of the interviews, data were internally validated, and the results were reported back to the interviewees, to facilitate the identification of fuzzy areas. Subsequently, the consensus was shared with the interviewees, for validation purposes.

The questionnaire survey was designed to classify the importance of the stakeholder concerns and social sustainability indicators identified above. Then, the survey was used as training samples, to obtain the BN parameters. This study used a chain referral sampling method, where all the respondents were selected based on their rich experience in GBPs. The questionnaire respondents included project managers, project engineers, professional designers, etc. This is due to their in-depth knowledge of green building and the fact that their concerns had a substantial impact on project sustainability level (Wu et al., 2017). **Table 3** shows the demographic information of respondents. The data were measured by a 5-point Likert scale, where one represents very less important, and five represents very important. A total of 205 questionnaires were distributed, from November to December 2019, and 147 valid questionnaires were collected in total. Then, STATA15.1 software was used to perform a statistical analysis on the questionnaire, in order to ensure internal consistency. The Cronbach's α coefficient is 0.899, which exceeds 0.80. This finding indicates that the inherent reliability of the questionnaire is reasonable. The KMO value is 0.871, which exceeds 0.8, indicating that the validity of the factor analysis is also very good. The Bartlett test result is $p < 0.001$, which is significant. This finding indicates that the validity is good, and factor analysis can be performed. Therefore, this questionnaire is credible and meets the requirements of statistical analysis.

4.3 Bayesian Networks-Based Model for the Case Study

The establishment of a BN model generally follows two steps. The first step obtains the structure of the BN, based on expert experience and the results of the structure learning algorithm. The second step obtains the parameters of each node of the BN through expert formulation and a parameter learning algorithm. A semi-structured interview was used to determine the causal relationship between stakeholder concerns and social sustainability indicators, in order to construct the BN. Then, the training data set was obtained via the questionnaire survey, in order to achieve the parameter learning of the BN, the probabilities of various node states were obtained accordingly. When the BN structure was known and the data were complete, MLE was applied, in order to estimate parameters through **Eq. 1**. The EM method was used to analyze missing data, obtain effective CPT parameters, and complete BN parameter learning. The steps in EM followed **Eqs 2–4**.

Based on previous stakeholder concerns and the identification of social sustainability indicators for the WHICC project, the potential causal relationships between them are identified. This study used the MLE algorithm to obtain the BN parameters from the training samples obtained in the questionnaire survey. Each node has three states, namely State 0, State 1, and State 2, which in turn correspond to high, medium, and low sustainability levels, respectively. If the probability of State 0 for this node is higher, this indicates this type of stakeholder concern or social sustainability indicator can highly improve the social sustainability level of the project, and vice versa. The

TABLE 2 | Detailed information of the interviews.

No	Stakeholder groups	Role	Work experience (years)	Interview time length (mins)
1	Government	Site supervisor	11	21
2	Main contractor	Project manager	16	37
3	Main contractor	Vice project manager	15	44
4	Main contractor	Safety supervisor	12	31
5	Consultant	Professor A	17	46
6	Consultant	Professor B	12	39
7	Developer	Project manager	22	28
8	Developer	Safety manager	15	23
9	Developer	Production manager	16	29
10	Designer	Senior engineer	25	33
11	Designer	Deputy chief engineer	20	35
12	Consultant	Senior consultant	10	42
13	Research institution	Researcher	25	30

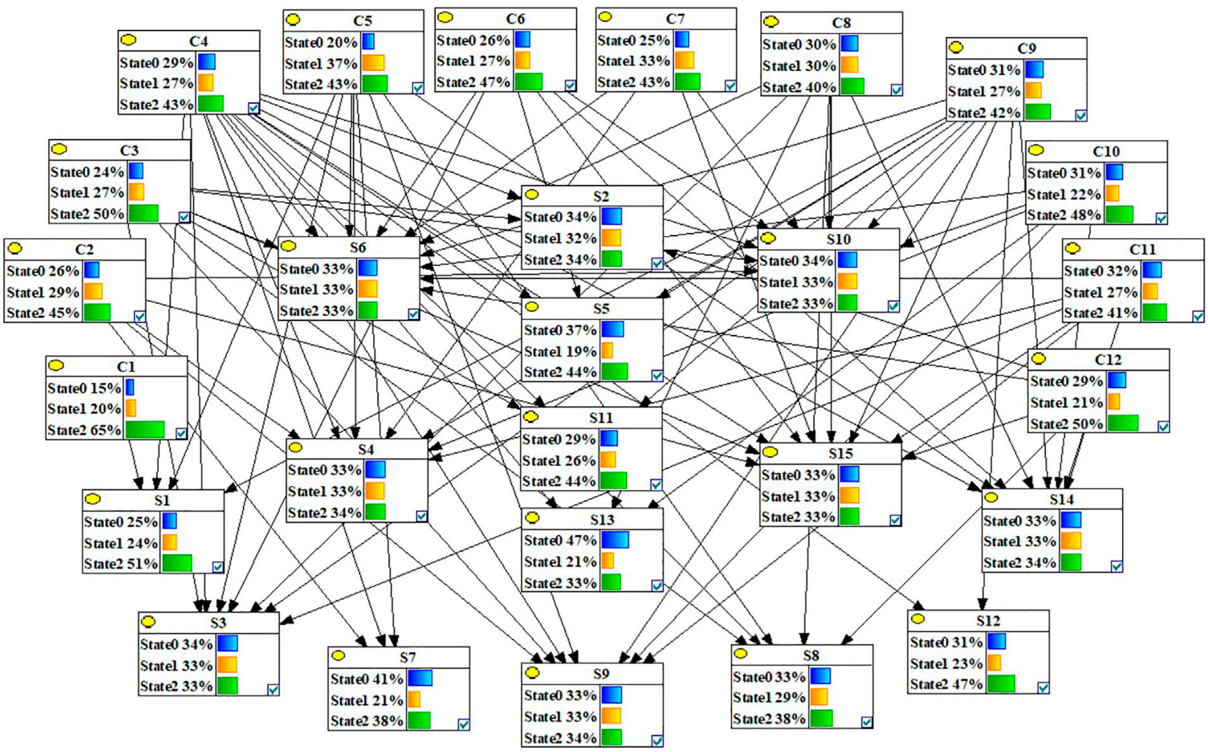

FIGURE 4 | Parameter learning results of the case study.

software GeNIe 2.3 was applied to analyze the training samples and run the BN model, as shown in **Figure 4**. The model is shown to consist of 27 nodes, including 12 stakeholder concerns and 15 social sustainability indicators that could promote the project sustainability of the WHICC. In **Figure 4**, numbers C1-C12 represent stakeholder concerns, while S1-S15 represent social sustainability indicators, the arrows indicate causal relationships among different nodes. The BN node number and explanation are shown in **Table 4**.

4.4 Results of the Case Study

The conditional probability distribution of each node is obtained through parameter learning, the social sustainability indicators are classified into three levels: low, medium, and high. In **Figure 4**, State 0 represents high, State 1 represents medium, and State 2 represents low. Then, BN parameter learning is divided into two stages: the initialization of the parameter and the matching of the access data with the BN. The initialization parameter is set to the average value 1/3 to realize the uniform distribution of the probability value of each node. Before

TABLE 3 | The demographic information of respondents.

Characteristic	Category	Frequency	Percentage (%)
Gender	Male	92	62.59
	Female	55	37.41
Designation	Project engineer	49	33.34
	Project manager	84	57.14
	Professional manager	14	9.52
Group	Government	31	21.08
	Developer	21	14.29
	Main contractor	27	18.37
	Designer	12	8.16
	Other	56	38.1
Work experience	<5 years	73	49.66
	6–10 years	46	31.29
	11–20 years	27	18.37
	>20 years	1	0.68

TABLE 4 | Bayesian network (BN) node numbers and descriptions.

Nodes	Descriptions
C1	Job opportunities created by the project
C2	Developed transportation network
C3	Conveniently service facilities surrounding project
C4	Green design and construction
C5	Aesthetic design of the building
C6	Qualified green building technology
C7	Green building project experience of the project team
C8	Safety at the construction site
C9	Abundance and stability of project funds
C10	Effective decision-making of the project team
C11	Mutual trust and understanding among stakeholders
C12	Effective communication between the project team and end-users
S1	Employment opportunity
S2	Minimizing neighborhood disturbance
S3	Health and safety
S4	Achievement of job satisfaction
S5	Market supply and demand
S6	User and owner satisfaction
S7	Not in my backyard (NIMBY) syndrome
S8	Public acceptability
S9	Social benefits
S10	Education and training
S11	Wages and welfare
S12	Anti-corruption and fair competition
S13	Obeying laws and regulations
S14	Promoting the development of the industry
S15	Stakeholder engagement

importing the data into GeNIe software, the data must be standardized via Access software, all of the software standardization results were then matched. The MLE algorithm does not require a priori probability values and can be executed by importing data from Access. Therefore, this algorithm was selected for this study. **Figure 4** also shows the parameter learning results of this case.

In addition, this paper calculates the strength of the influence between parent nodes (i.e., stakeholder concerns) and child nodes (i.e., social sustainability indicators), according to previous parameter learning results. The strength of influence in this study indicates the strength of the influence a parent has on a child. Here, "influence" essentially expresses a specific form of distance between various conditional probability distributions on child nodes, conditioned on the states of the parent node. **Table 5** shows the 10 strongest influences. As a result, green design and construction (C4), convenient service facilities surrounding the GBP (C3), and abundance and stability of project funds (C9) all exert a significant impact on wages and welfare (S11). Therefore, the project team should focus on these stakeholder concerns and increase wages and welfare accordingly, in order to improve the social sustainability level of the project.

Diagnostic analysis *via* **Eq. 5** identifies the posterior probability distribution of each indicator once the sustainability criterion is reached. According to the results of the strength of their influence, the State 0 of node S11 was set to 100%, i.e., the high level of wages and benefits that meet the socially sustainable evaluation criteria are certain. The results are depicted in **Figure 5**. As a result, nodes C3 (convenient service facilities surrounding the GBP), C4 (green design and construction), and C9 (abundance and stability of project funds) are influenced by node S11 (wages and welfare). Specifically, the probability of State 0 for node C3 changes from 24 to 15%, the probability of State 1 for node C4 changes from 27 to 22%, and the probability of State 1 for node C9 changes from 31 to 18%. These findings indicate that the sustainable performance of the project can be more effectively increased by changing these factors.

The sensitivity analysis analyzes and calculates the change of the parent node when the child node of the network changes, the analysis also identifies the parent node that has a greater impact on the child node. **Figure 6** shows the sensitivity analysis result of the BN-based model, which used S9 as the target node. The dark-colored box indicates a sensitive factor. Nodes C2, C3, C4, C5, C9, C10, and C11 were identified as sensitive stakeholder concerns. This indicates that these concerns impose significant effects on S9 (social benefits). Therefore, the sustainability level of social welfare can be improved by changing these stakeholder concerns.

However, since S9 can only represent one aspect of the social sustainability level, other sustainability indicators must necessarily be assessed. To increase the comprehensiveness of the results of the sensitivity analysis, all stakeholder concerns introduced in this paper were analyzed. That is, all indicators were analyzed step-by-step, the union value was taken, and **Eq. 6** was used to calculate the sensitive performance. In **Figure 7**, C4 (green design and construction), C9 (abundance and stability of project funds), and C3 (convenient service facilities surrounding the GBP) were identified as the three most sensitive stakeholder concerns. Accordingly, these three sensitive stakeholder concerns should receive major attention, given their significant effect on the overall social sustainability level of the GBP.

4.5 Model Validation

This study adopted the validation framework proposed by Pollino et al. (2007), who refers to the concept of "sensitivity to findings". This method can test the predictive validity of

TABLE 5 | Ranking of the influences according to factor strength.

Ranking	Stakeholder concerns	Social sustainability indicators	Strength of the influence	
			Weighted	Maximum
1	C4	S11	0.3501	0.7087
2	C3	S11	0.3399	0.6535
3	C9	S11	0.3079	0.6292
4	C12	S2	0.2965	0.6000
5	C10	S13	0.2910	0.5728
6	C4	S2	0.2879	0.5358
7	C3	S2	0.2697	0.5568
8	C4	S13	0.2633	0.5204
9	C8	S13	0.2559	0.5358
10	C4	S5	0.2546	0.5774

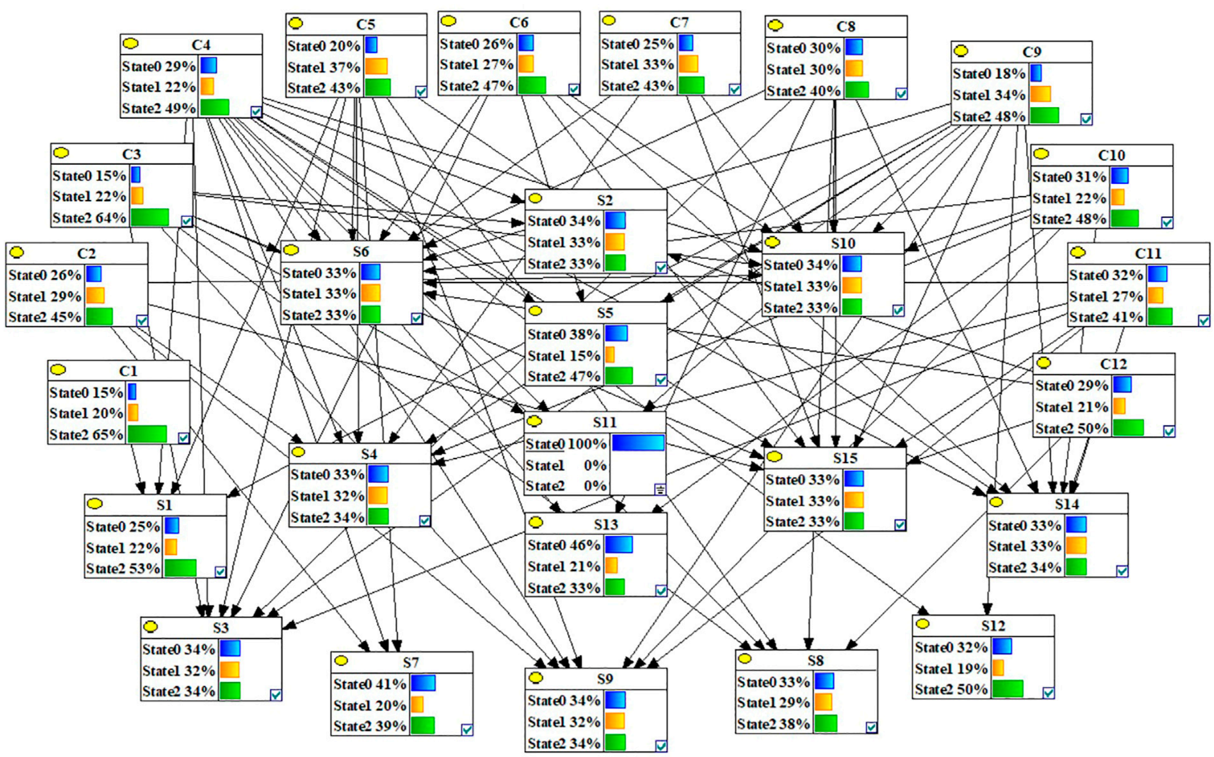

FIGURE 5 | Diagnostic analysis results of the case study.

expert-elicited networks by analyzing the degree of consistency between critical factors and sensitive factors. This method has been widely used in various BN-based studies (Pitchforth and Mengersen 2013; Yu et al., 2019). Therefore, this technique is used in this study to validate the SCSM model based on BN. The case study showed that C4 (green design and construction), C3 (convenient service facilities surrounding the GBP), and C9 (abundance and stability of project funds) were the key stakeholder concerns that significantly influence social sustainability. In the diagnostic analysis of the BN, C3, C4, and C9 were additional important concerns, affecting the social sustainability performance of the WHICC project. Concerning the sensitivity analysis of S9 (i.e., social benefits), the results show that C3, C4, and C9 are included in the sensitive concerns. In addition, S11 (i.e., wages and welfare), S2 (i.e., minimizing neighborhood disturbance), S13 (i.e., obeying laws and regulations), and S5 (i.e., market supply and demand) are identified as influential social sustainability indicators (**Table 5**). **Figure 4** shows that C3, C4, C9, C8, C10, and C12 are linked with these nodes. This implies that these sensitive stakeholder concerns are closely related to the key social sustainability indicators, which in turn further

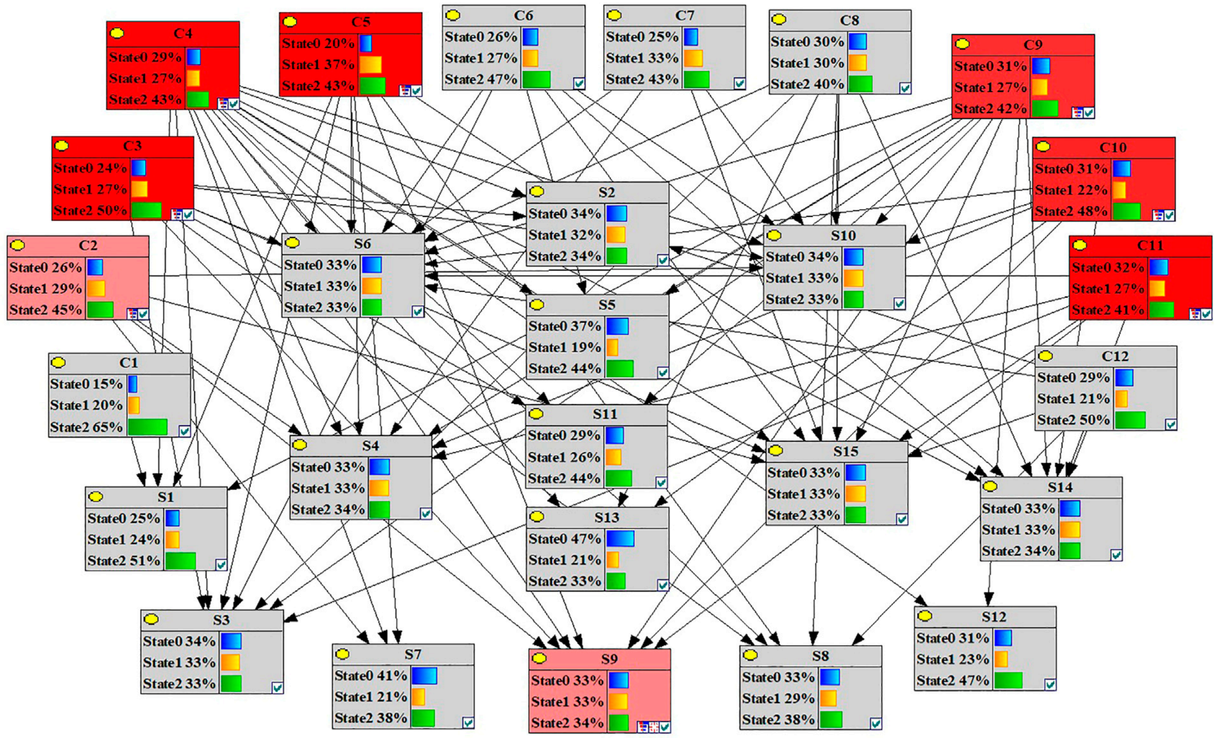

FIGURE 6 | Sensitivity analysis results of the case study.

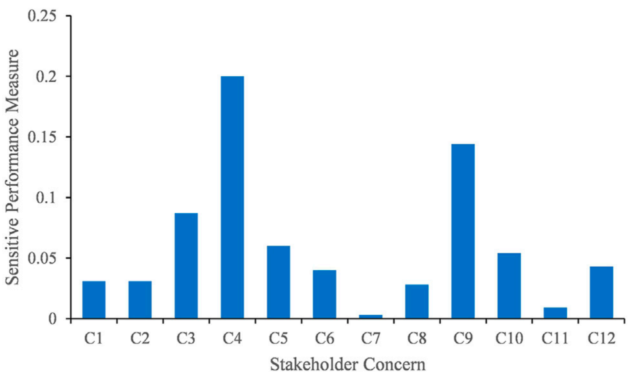

FIGURE 7 | Ranking of stakeholder concerns according to the case study sensitivity analysis.

supports the results presented above. In summary, the strengths of the influence analysis, diagnostic analysis, and sensitivity analysis were highly consistent, thus strongly verifying the reliability of the data analysis. Following this verification, the results were fed back to the 13 previously-interviewed experts, to evaluate the credibility of the results. As a result, most of the experts (at least 7) supported the key stakeholder concerns identified in this case. Furthermore, to ensure the validity of the BN model, this study asked experts for the reasons why they agreed or disagreed with the results (Yu et al., 2019).

5 DISCUSSIONS

Existing stakeholder management frameworks have primarily focused on representing various aspects of project complexity, risk, and sustainability (Zhao et al., 2016; Mok et al., 2018; Bohari et al., 2020). Despite the fact that a few studies have focused on the complexity of stakeholders and their concerns (Mok et al., 2017b, 2018; Tang et al., 2018), until now, no attempt has been made to adequately capture the interdependency between stakeholder concern and social sustainability (Chen et al., 2021a; Wu et al., 2021a; Wu et al., 2021b). As a result, there is a need to develop a decision-making model that recognizes the importance of interdependency within complex stakeholder concerns in order to achieve social sustainability. SCSM makes an effort to contribute to this new approach. With regard to social sustainability management in construction projects, the importance of decreasing travel time and the availability of amenities have been highlighted before Sierra et al. (2018). This study also identifies C3 (i.e., convenient service facilities surrounding the GBP) as a key stakeholder concern. One can see that both traditional construction projects and green construction projects must increase investment in convenience facilities and services if they are to increase their level of social sustainability. A project manager in this case study reported that, “Convenient transportation and basic service facilities are very important. This is mainly because the procurement and transportation of building materials will take a long time. If there is no developed transportation network in place, transportation will become an enormous problem." Next, basic service facilities should be improved so that they meet the basic living needs of managers and workers on site. For example, due to site restrictions, there is no employee restaurant, and thus, employees need to go out to buy their food. However, there is no supporting restaurant nearby, so their work is greatly hindered.

The abundance and stability of project funds are also significant factors for sustainability decision-making. This result is consistent with Qazi et al. (2016), who addressed stakeholder complexity in order to identify major pitfalls in large cultural building projects. To facilitate sustainable design and construction, adequate financial support is an essential prerequisite. Construction projects commonly face problems of financial instability, this issue was also identified in this case study. The design and construction stage involves many wearisome processes, such as design changes, claims, and acceptance, all of which induce many uncertain factors that can affect the stable payment of funds. In this case study, many unfavorable consequences were caused by insufficient funds. For example, project team members became frustrated, workers could not be recruited, and there was even disruption at the construction site. Therefore, adequate and stable financial support forms the basic guarantee for increasing the social sustainability level of GBPs.

In this case study, green design and construction play an important role in improving the social sustainability level of the project. This result is inconsistent with those of Li et al. (2012), who reported that most of the rankings for this stakeholder concern are low. The main reason for this conflict in findings is that the research background of both studies differs. The research of Li et al. (2012) focused on large public infrastructure projects, while the present study focuses on GBPs. Firstly, the stakeholders involved in the project have different concerns. Public infrastructure projects are usually organized and implemented by governmental departments. These pay more attention to the employment opportunities, economic benefits, and regional economic development induced by the project. Therefore, projects of this nature often ignore sustainability issues. Secondly, in the case of the Wuhan GBP, the concept of green and sustainable development was determined at the initial stage. To meet the evaluation standards of green buildings, many advanced technologies and materials have been applied. These evaluations involve every stage of the project, thus, the project leaders have to thoroughly evaluate each acceptance standard and refine any relevant processes that do not meet these criteria. As such, this project ultimately reached the three-star standard of green building by implementing green and sustainable construction into the whole life cycle.

In existing empirical studies BN has been widely employed in project risk management (Chen et al., 2021b; Koseoglu Balta et al., 2021). However, very few studies have used the technique to manage project sustainability. The frequently-used methods of social network analysis (SNA), analytical network process (ANP), and structural equation modelling (SEM) (all of which are used to model stakeholder involvement and project complexity) can explain the interrelationships between stakeholders. However, these methods are stretched when faced with how two related factors behave according to each other's changes. This paper refers to other experts' experiences and implements Bayesian inference to address this problem (Qazi et al., 2016; Bakshan et al., 2017; Yu et al., 2019). Furthermore, few studies on social sustainability are available, the level of social sustainability is also difficult to quantify. Compared with previous studies on stakeholder concerns and social sustainability indicators (Mok et al., 2018; Goel et al., 2020; Yadegaridehkordi et al., 2020; Zhang and Mohandes 2020), this paper integrates both and analyzes the uncertain relationship between them. By using BN to model this uncertain relationship, the most important stakeholder concerns—i.e., those that affect the social sustainability of the project—are identified. The accuracy of project decision-making is also improved by employing optimal sustainability improvement strategies. This paper proposes an exploratory effort to address the uncertainty problem of GBPs' social sustainability, as well as a SCSM analysis approach for a real-world case. In addition, a solid reference for sustainable management decisions of similar projects is also provided. Managers can visualize the interaction between stakeholder concerns and social sustainability, they can also appreciate propagation patterns through sustainability paths and locate key concerns, thus promoting the success of a project's sustainability management.

6 CONCLUSION

The complexity of stakeholder concerns can hinder decision-making, thereby further affecting the sustainability level of GBPs. Through a review of the literature on stakeholder concerns and interdependency modeling of social sustainability in GBPs, this study establishes a major research gap, namely establishing an SCSM process, exploring the interdependency modeling of stakeholder concerns-driven social sustainability. The illustrative application of this approach gives an insight into understanding the dynamics across the entire spectrum of sustainability management. Specifically, this paper uses literature reviews, semi-structured interviews, questionnaires and obtained data to analyze stakeholder concerns and social sustainability indicators. The probability and causality of the network nodes are identified according to the results of interviews. Then, a BN model is established, and a BN diagnostic analysis and sensitivity analysis are used to identify the stakeholder concerns that have the greatest influence on the social sustainability goals. A project case in Wuhan is used to test the SCSM model for decision-making. The results identify green design and construction, convenient service facilities surrounding the project, and the abundance and stability of project funds as the three main stakeholder concerns that exert a significant impact on the social sustainability level of the GBP. These findings confirm that project managers should consider the complex interaction between project sustainability objectives and stakeholder concerns, rather than relying solely on past experiences with GBPs. Through the use of BN decision-making analysis, the findings of this work contribute to the social sustainability of the green building industry and open up new research avenues. This study also establishes an SCSM framework for a real-world case, which can be used as a guide for making sustainable management decisions for comparable GBPs.

7 IMPLICATIONS

In theory, according to previous research on GBPs (Qazi et al., 2016; Mok et al., 2018), interactions between different stakeholders and their individual concerns are characterized by uncertainties. The SNA, ANP, and SEM methods are widely used in relevant research to analyze the interrelationships between stakeholders, as well as to determine their importance. This is achieved by analyzing their position within the network. However, these types of research do not and cannot reflect the impact of uncertainty. The present study uses a BN-based model to simulate the realization of project uncertainty sustainability evaluation indicators. Using this model, the influence of stakeholder concerns is investigated, based on relevant changes. This study also bridges the areas of stakeholder concerns and social sustainability. As previously stated, there is a scarcity of study on the social sustainability of GBPs, and one of the reasons for this scarcity is the limits imposed on data acquisition. Collecting data related to the complex dynamic relationship between stakeholders is complicated, and this, coupled with non-quantifiable nature of social sustainability, makes this a particularly difficult study challenge. Based on the successful application of the BN in construction project risk assessment, this paper extends this assessment to a sustainability assessment of GBPs. This constitutes exploratory efforts to solve the uncertainty problem of social sustainability.

In practice, the research results of this article provide the project leader with more precise control of the project's sustainability level. First, this paper identifies the indicators and stakeholders that may affect the social sustainability of the project. Project managers can use these indicators and concerns to control project quality. These indicators can be collated into a checklist, which project implementers can use to identify and specifically focus on the identified issues during the construction process, thereby reducing the need for revision. Second, this paper uses the BN model to identify key stakeholder concerns, specifically, those that exert a significant impact on social sustainability. Project leaders can focus on these concerns, which will help them to better understand the different concerns of project participants and to make more effective decisions. For example, project decision-makers can provide convenient public service facilities and effective services for project participants, which will help to improve the participants' work performance. Third, the SCSM framework proposed in this paper can be used to assess the stakeholder concerns when faced with project social sustainability issues. Based on these concerns, project decision-makers can better understand the needs of project participants and adopt reasonable strategies to increase their awareness of social sustainability. This understanding will ultimately improve project sustainability performance. Fourth, this decision-making method can be applied to the environmental and economic sustainability assessment of the project. When confronted with a specific case, the same process can be used to identify variables and create causal links, resulting in a sustainable strategy that is unique to and appropriate for the project.

8 LIMITATIONS AND FUTURE WORKS

This study has some limitations. First, in the process of the identification of stakeholder concerns and social sustainability indicators, this study relied on questionnaires and interviews when determining their causality. This process is very laborious and increases the subjectivity of the results. In future studies, large samples of data can be collected instead and entered into the model to produce more objective results. Second, the SCSM approach is applied in a GBP located in Wuhan, the results may not be suitable for other types of industries because more concerns may emerge with the complexity of construction projects. Future work will validate the approach in the context of different industries and take more project-based stakeholder concerns into consideration through case studies to get a deeper insight into how the social sustainability can be improved in GBPs.

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

SW wrote the first draft of the manuscript. GQ contributed to the conception and design of the study. All authors discussed the results and contributed specific knowledge of the relevant literature.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.874367/full#supplementary-material

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How to Improve Environment Performance? The Comparison of Stakeholder Perceptions on How to Improve Air Quality in China

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The air quality and carbon neutrality strategies in China has attracted the growing concern of multiple stakeholders. Through face-to-face surveys conducted in five major cities in North China, we compared the stakeholders' perceptions. Our research reveals conflicting perceptions among stakeholders. On the one hand, local authorities and academics prefer to focus on market-based regulation to prevent air pollution. Enterprise managers, however, do not want to be regulated. On the other hand, social groups expect more information about air pollution to be released, but local authorities do not see releasing that information as a top priority. These differences of perceptions can actually be useful in terms of policymaking.

Keywords: perception, air pollution, comparison, stakeholder, China

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INTRODUCTION

Along with rapid urbanization, the air pollution problem in China has drawn wide concern from different social sectors. For example, the hazy weather that appeared in almost all provinces in 2021 has focused the attention of local governments, citizens, non-government organizations and other organizations. These parties assessed the damage caused by the hazy weather and made suggestions for improvements. However, we should know that the relationship between air pollution and its effects are mediated by people's perceptions (e.g., interpretation and response) of the air quality (Kasperson et al., 1988). This fact has driven the development of research into risk perceptions. In this instance, risk perception is a human being's evaluation of the level of risk in a situation, associated with the uncertainty of that risk. Air pollution causes risk perception. Essentially, air pollution affects the attitudinal process that tries to understand the gap between expert and lay perceptions of environmental risk. Pollution is also related to broader social factors and processes. These factors include locality, agency, trust and communication (Bickerstaff, 2004). However, assessing the quality of environment services for different stakeholders is difficult, because every person has his or her own risk perception and risk-bearing capacity. The attitudes of an individual toward risk can only be understood when associated within a specific context (Acedo and Florin, 2007).

We should know, however, that the perspective of a stakeholder's subjective perception is important, because that perspective and perception tells us the degree of awareness among people. That is important information for policy makers to have, as they attend to the problem of how to reduce air pollution. Stakeholders can also be seen as part of the problem. In many cases, a change in their attitudes and behavior is needed. Many studies have shown that the perceptions of stakeholders are useful with regard to policy development (Chanthawong and Dhakal, 2016). For instance, the existing approach to environmental policy-making in China is top-down. The existing approach also lacks integration across different government agencies and other stakeholders. This type of approach means governments cannot effectively address the complexity of environmental problems. In addition, the perceptions of experts and think tanks could make any new policy more scientific and objective. What needs to be pointed out, then, is that the stakeholders should be selected carefully. The wrong stakeholders' perceptions and participation may not result in greater environmental policy outcomes (Newig and Fritsch, 2009). One reason for this fact may be that some stakeholders' perceptions are non-scientific. However, even non-scientific perceptions can actually lead to a more democratic result (Maier et al., 2014). Democracy is also important in terms of policy-making. Therefore, we should incorporate different perceptions of both a scientific and democratic nature. Taking into consideration the perceptions of citizens is a democratic approach.

This paper aims to evaluate the perception of air pollution in order to improve air quality on the basis of a stakeholder perspective. The main research questions are: What are the perception differences between stakeholders? Also, what are the differences in their (the stakeholders') suggestions on how to improve air quality?

The remainder of this article is structured as follows: The literature review highlights the importance of using the stakeholders' perspectives to address the problem of air pollution. The following section presents the theory frameworks. The methodology section clarifies the methods of data collection and analysis. The subsequent section describes the research findings. Finally, the last section of this paper presents our conclusions, which concludes with the main contributions.

BRIEF HISTORY OF AIR POLLUTION PERCEPTIONS RESEARCH

The earliest studies of public attitudes to air pollution were conducted in the 1950s and 1960s. These studies used social survey techniques to research public perceptions, in order to investigate the possible relationship between air pollution and health. For instance, Smith et al. (1964) collected opinions from nearly 3,000 people to discuss their concerns about the possible adverse effects of air pollution on health. The Smith study recommended that governments should rely on purely technical solutions to solve the air pollution problem (Groot, 1967).

Owing to a dozen special television broadcasts, numerous magazine reports and environmental groups efforts, the spring of 1970 was a milestone in the effort to increase public awareness of environmental problems (Murch, 1971; Gray et al., 1973). The general thinking was that the public would play a major role in reducing air pollution. Therefore, multiple studies investigated the perceived damage from air pollution and the ways to reduce the associated problems. Proposed solutions included assessing people's willingness to donate money to support a public effort to combat air pollution. However, few studies continued to focus on air pollution during the 1980s. The studies during that decade paid more attention to other environment issues, such as global warming and acid rain (Saksena, 2011).

After 1990, there was renewed interest in researching the air pollution issue. Those studies, however, delved much deeper into the issue than ever before. The researchers realized that environmental indicators played an important complementary role in air quality observations (Cole et al., 1999). They were also aware of the fact that air quality information was an important means by which to effect perceptions and behavioral changes (Beaumont et al., 1999; Bickerstaff and Walker, 1999).

After 2000, more and more research focused on how the social, cultural and economic contexts (such as sex, age and education) could affect the public's experience of air pollution (Bush et al., 2001; Bickerstaff, 2004; Kan et al., 2008). For instance, Badland and Duncan (2009) showed those people who were more highly educated or who were living in major cities were more likely to recognize the fact that air pollution harmed their health. Kim et al. (2012) found that the degree of perceived air pollution was higher among those of a younger age, a higher level of education and a lower household income. In addition, Ngo et al. (2017) found that participation in solving the problem could help residents understand air pollution and help them develop a response to that pollution. Those facts indicate that the research of air pollution perceptions is a multidisciplinary study.

This paper argues that any effort to improve air quality should take into consideration the multiple and sometimes conflicting perceptions of all correlated stakeholders. These stakeholders may have conflicting viewpoints on how to improve air quality, because of their different social, cultural and economic backgrounds and experiences. Under such conditions, this paper uses the theory of cognitive conflicts to develop an integrated framework that describes the perception differences of academics, local authorities and local citizens.

ENVIRONMENT PROBLEM PERCEPTIONS AND COGNITIVE CONFLICT

From the above section, we know that stakeholders may have different perceptions of the air pollution problem. Their perceptions may vary with regard to the existing or potential future problems of air pollution (the consequences, causes and demarcation of the air pollution problem). Opinions may also vary with regard to the possible situation (possible changes and the availability of solutions to the air pollution problem), the desired situation and the yardsticks by which to evaluate the existing situation (Koppenjan and Klijn, 2004). The above facts clearly indicate that the stakeholders do not share a common problem definition. As such, their perceptions are difficult to change, because they are based on the frame of reference of each individual, organization or group involved. In reality, solving the problem of air pollution problem will require cooperation from all parties. However, many of the partners often hold different perceptions and measure the problem and potential solutions with different yardsticks. These different perceptions entangle the partners, resulting in an asymmetrical frame of mind. This condition, in turn, causes misunderstanding and conflicts. We call this cognitive conflict. Therefore, cognitive conflict occurs

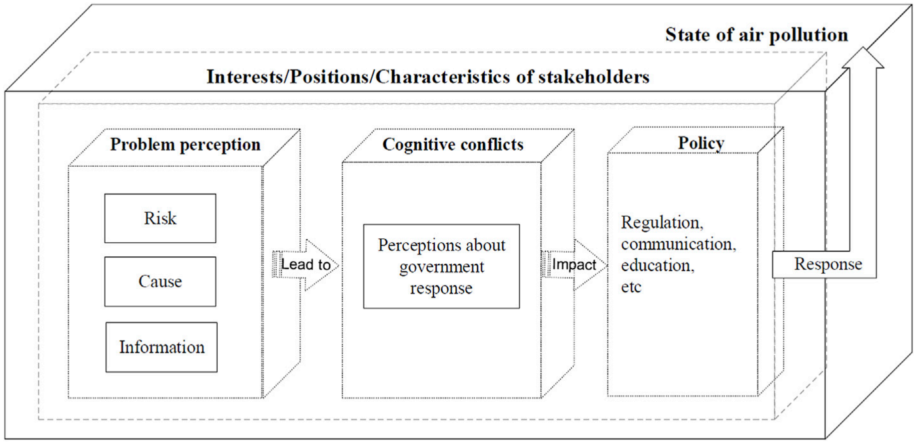

FIGURE 1 | A logic model approach to air pollution perception analysis.

when partners or stakeholders discuss and debate their various preferences and opinions about the same problem or task (Mooney et al., 2007).

Cognitive conflict makes cooperation difficult. However, this does not mean that this kind of conflict should be abandoned. Everything has two sides. The stakeholder debates may in fact promote better decision making, because these debates may force governments to synthesize multiple environmental views. Many studies have proved that cognitive conflict can promote the exchange of ideas, encourage the understanding and acceptance of each other, and then improve the quality of decision-making and democracy (Amason, 1996).

Those conflicting relationships are considered in the framework for analysis presented in **Figure 1**. *State of air pollution* represents the survey participants' perceptions of the state of air pollution. Here, air pollution means the physical, chemical and biological changes of air quality caused by haze. *Interests/positions/characteristics of stakeholders* describes the cultural and educational background of the stakeholders. Some studies have found that local knowledge (obtained through social interaction) plays an important role in shaping perceptions (Howel et al., 2003). *Problem perception* represents symptoms, which relates to stakeholders' perceptions of air pollution risks, effects, causes and so on. This category includes the perception relating to the causes and sources of pollution, the risk perception of stakeholders and the risk bearing capacity. *Cognitive conflict* represents the stakeholders' view on how the government should respond and intervene in the air pollution issue. The stakeholders' different perceptions of air pollution make up their cognitive diversity. *Policy* means the government's response to the air pollution symptoms. Any policy must address the perception risks, effects and causes that must be targeted by regulation, market instruments, communication, and/or education.

The above framework is based on a concept of causality that implies the public's experience of haze induces their problem perception. Different perception will lead to cognitive conflict. Those cognitive conflict may be useful for policy-making. In a wider sense, the framework forms an environmental policy cycle that includes experience perception, problem analysis and policy response.

METHODS

Study Areas

Our study areas focus on cities in the north of China (including Shanxi, Hebei, Liaoning, Jilin, and Heilongjiang provinces). The focus areas include *Taiyuan* city, *Shijiazhuang* city, *Dalian* city, *Changchun* city and *Harbin* city, which are located in Shanxi Province, Hebei Province, Liaoning Province, Jilin Province, and Heilongjiang Province, respectively. The North area is an important center of heavy industries and the coldest region of China. winter temperatures can dip to around -40 ˚C in *Harbin* and *Changchun*. This area has more air pollution problems than other areas of China. Especially in the winter, the north area has no choice but to consume more coal for heating purposes. Both the concentration of heavy industries and the burning of extra coal in the winter make the air quality of the north cities a serious problem.

Survey Development

Our survey consisted of questions on people's perception of the level of air pollution, their perception of the risk to health posed by air pollution, and their perception of how governments should respond to the pollution. We expected the respondents to complete the survey in about 30 min. We adopted a mixed-methods design, which included a survey of the stakeholders. The survey was followed by semi-structured interviews with the stakeholders. The first part of the questionnaire captures each respondent's information. From this, we learn the context of each stakeholder. The second part includes 12 questions (see **Table 1**). These questions are used to test our framework in **Figure 1**. From questions 1 to 9, we conducted a structured interview. These questions have only a limited number of possible answers. From questions 10 to 12, we conducted a semi-structured interview. These are open questions.

Participants and Data Collection

The data collection for the five cities was completed through face-to-face interviews, from 2018 to 2020. The social construction

TABLE 1 | Illustration of stakeholders' survey.

Information of Respondents	–	Questions
State of air pollution	Q1	How is the air pollution in your living city?
	Q2	Do you think the air quality is more serious than 3 years ago?
	Q3	How much attention have you paid to air pollution?
Problem perception	Q4	Do you think air pollution poses a health risk to your body and your family?
	Q5	What are the air pollution sources in your living city?
	Q6	From which channels can you get information on air pollution?
	Q7	Do you think the information about air pollution prevention is adequate?
	Q8	What actions have you taken to reduce the risk of air pollution?
	Q9	Do you know of some policies for the prevention of air pollution?
Cognitive conflict and policy	Q10	How do you think you could prevent air pollution effectively?
	Q11	Could you give some advice to the Department of the Environment? What advice do you think is most important?
	Q12	Which departments do you think should be responsible for air pollution?

theory addresses the ways we think about and use categories to structure our experience and analysis of the world. Similarly, we used this theory as a principle by which to select two scientifically and presumably objectively-oriented stakeholders (local authorities and academics), in contrast with two more subjectively-oriented stakeholders (enterprise managers (lobbying groups) and social groups) (Lim et al., 2016).

The term *local authorities* refers to the Commission of Development and Reform (CDR), and the Department of Transport (DT). The former is in charge of the affairs leading to the approval of investment. Therefore, the CDR is related to and responsible for the solving the problem of air pollution from industry. The latter (DT) is related to air pollution from transport. Some studies have focused solely on air pollution from industry and traffic (Geelen et al., 2013). *Enterprise managers* refers to the managers who work in the machinery and energy industries. These businesses will, of course, be affected by the outcome of any new and relevant environment policies (Althoff and Greig, 1974). *Academics* refers to the scholars who carry out research related to the environment. We believe that these academics have the necessary expertise in air pollution prevention. *Social groups* refers to media, and the media refers to people who work in local newspaper offices, TV stations and radio stations. Local authorities and academics have objective information on air pollution and the associated risks. These authorities must also uphold public health standards. Enterprise managers, as the interest groups, care more about the economics of production, while the language of the public and media may show the most subjective and varied perceptions of air pollution (Lim et al., 2016).

As Lim et al. (2016) describes the stakeholder role in policy changes and debate (as outlined above), we have some expectations about what types of language will be used by each stakeholder.

- Expectation 1: Local authorities have professional departments to monitor air quality. These authorities have the ability to acquire pollution information. We suppose that their perceptions are objective.
- Expectation 2: Enterprise managers' perceptions may vary across different industries. The machinery and energy industries in the north of China are highly polluting. The enterprises are also profit-oriented. We suppose that the enterprise managers' perceptions on how to reduce pollution are subjective.
- Expectation 3: Academics would present objective information on their air pollution perceptions. We suppose that their perceptions are objective.
- Expectation 4: Social group perceptions generally care about the risks and effects of pollution. However, these groups do not have enough information. We suppose, therefore, that their perceptions are more subjective.

All the interviewed stakeholders are working and living in the five cities. As such, they are familiar with the state of their local air quality. The entire sample group consists of non-probability sampling selected. We adopted the method of snowball sampling, i.e. asking the initial interviewees to suggest other important participants for further interviews (Hysing, 2015). In these interviews, we obtained more detailed information regarding the perception of air pollution. We interviewed 105 respondents over 2 years period.

RESULTS

Stakeholder Perception of the State of Air Pollution

Question one is "*How is the air pollution in your living city?*" From our investigation, we can see that 75% of respondents think their city's air pollution varies on a seasonal basis. They say the air pollution will be serious in the winter. Furthermore, we can see that the percentage of enterprise managers who feel air pollution is a problem is the highest, followed by the academics and social groups. No one thinks the air is clean. Question two is "*Do you think the air quality is more serious than 3 years ago?*" Here, 69.4% of respondents think air pollution is more serious than it was 3 years ago. For this question, the percentage of local authorities who feel pollution is worse is the highest. Question three is "*How much attention have you paid to air pollution?*" Here, 54.2%of respondents care about the air pollution problem, especially the enterprise managers. Other respondents also show great concern about the air pollution problem. These results show that, even though stakeholders place difference emphases on the state of air pollution, most of them share the same perception (that air pollution is especially serious in the winter).

Stakeholder Perception on the Risk of Pollution

Question four is "*Do you think air pollution poses health risks to your body and your family?*" Most of the interviewees think air pollution poses health risks. Nearly all stakeholders have similar opinions on this question. Question five is "*What are the air pollution sources in your living city?*" For this question, 83.3% of the interviewees selected the heating and generating answer. They argued that a high energy-consuming industry makes the air pollution more serious. This was especially true of the enterprise managers. Likewise, additional research showed that none of the socio-demographic variables had significant differences in their perception of air pollution causes and effects in Mexico City (Landeros-Mugica et al., 2014). Question six is "*From which channels can you get information on air pollution?*" Most of the respondents selected the media as their major source. In the age of the internet, people can easily collect information more widely and rapidly. Question seven is "*Do you think the information about air pollution prevention is adequate?*" Here, 84.7% of the interviewees said they do not have enough information to prevent pollution. From this result, we can see that none of the enterprise managers currently receives enough information to prevent air pollution. Other stakeholders can, more or less, obtain enough information through various channels. Some studies have shown that open communication and/or stakeholder involvement are the keys to improving the perception of safety (Geelen et al., 2013). Question eight is "*What actions have you taken to reduce the risk of air pollution?*" Most stakeholders elect to wear masks and reduce outdoor activities. A few have taken steps to reduce emissions, such as driving less. Question nine is "*Do you know of some policies for the prevention of air pollution?*" Here, 44.4% of the respondents said they know of some policies relating to the prevention of air pollution. Other interviewees say that they want to know the policies, but they do not know how to obtain the information relating to those policies. Just as with the interviews conducted by Chen et al. (2017), many Chinese people expressed their sense of powerlessness when faced with air pollution.

Stakeholder Perception of How to Improve Air Quality

All of the surveyed academics think the most effective way to reduce air pollution is to reduce emissions. Most of the other stakeholders also think that emission reduction would be effective. However, from the answers to Question 8, we know that most of the stakeholders wear masks to protect their personal health, not to help in the reduction of emissions. We do not get the same answers to Questions 8 and 10. Therefore, gaps exist between the respondents' perceptions and their actions.

To discover the similarities of and differences between stakeholders' advice to the environment department, we used the content analysis method to study word frequency during the interviews. The local authorities argue that air pollution stems from a lack of regulation and education. They also think that emission reduction and energy conservation methods will play vital roles in the future prevention of air pollution. As such, they think the government should regulate the market and reduce emissions. At the same time, the public should be educated on how to save energy. The enterprise managers think that heating and car exhaust are the main sources of air pollution, followed by dust pollution and burning straw. In their opinion, the government should reduce pollution from those sources. For example, some managers stated that "*governments could disseminate the knowledge of how to prevent air pollution, and they should encourage the public to travel by public transport.*" Another stated, "*To save energy, government should replace decentralized heating with central heating in winter.*" The academics share the local authorities' opinions. They also see government regulation as the most important means to reduce air pollution. In addition, the academics advocate green travel, media exposure and public participation. As one professor said, "*Governments should regulate the enterprises. The public, the media and others can take part in the process of regulation.*" All of the social groups emphasize the importance of media exposure. Education is also seen as having an important role, as agree by the local authorities and enterprise managers. Then comes public participation, an opinion shared with the academics. "*Governments should release air pollution information to the public in time. They could organize the public to regulate the market and encourage citizens to reduce their exposure to pollution.*"

We again find some interesting results. Market-based regulation is seen by local authorities and academics as the most important way to prevent air pollution. However, such regulation is seen by enterprise managers as the least important way to prevent air pollution. This is clearly because the enterprise managers would be the ones to be regulated. They do not want to be supervised by regulators. In the eyes of the social groups, media exposure is the most effective way to reduce air pollution. However, only a few of the local authorities see media exposure as being important. Perhaps local authorities are afraid of having to deal with a crisis. Unexpectedly, all participants see punishment as the least important way to prevent pollution.

The last question is about which department should be responsible for reducing air pollution. It is often assumed that all relevant stakeholders agree that the department of the environment should be responsible. The reality, however, is more complex. Most of the respondents have given us their choices. Most enterprise managers selected the environment department. Half of the local authorities and the social groups also selected the environment department. Less than half of the academics think the environment department should be responsible for reducing air pollution. The main reason given by the academics for this opinion is that "*The environment department is good at the management of the environment, and they already have the right to punish the market (polluters) according to the Environment Protection Law.*" However, some of the stakeholders believe that multiple sectors should take responsibility for reducing air pollution. In addition to the environment department, the commission of development and reform, the department of transport and others were listed as potential contributors to the reduction of air pollution. The sources of air pollution are varied, and are related to multiple sectors. For example, one respondent stated, "*The environment department is responsible for industrial air pollution. The housing department is responsible for dust pollution* *from building construction. The police department is responsible for the transport emissions.*" In addition, a few respondents suggested that local mayors must take responsibility for reducing air pollution. After all, mayors in China have decision-making power with regard to industrial development and urban planning. Their philosophies and strategies determine the fate and future of a city. For instance, one respondent advised, "*It is necessary to set up a cooperation committee. The mayor is the leader and coordinator of the committee, with the multiple sectors as the members of the committee.*"

CONCLUSION

Due to the rapid rate of urbanization in China, people face more air environmental risks than during any other period in history. The public perception of air pollution is one of increasing concern. O'Connor et al. (1999) showed that knowledge increases people's willingness to take the necessary actions to address environmental problems. However, people grasp the necessary knowledge in different way, from different sources and at different levels. In addition, different people have a wide variety of backgrounds and social experiences. As such, many people have different perceptions of pollution and the related hazards. In this context, we construct a framework and take the case of north China to discuss stakeholder viewpoints and cognitive conflicts on the subject of air pollution. Some interesting findings follow.

Firstly, all of the stakeholders admit the reality of air pollution and its risks. Most of them choose to wear a mask to protect themselves from air pollution. Why is their behavior not consistent with their perceptions? One possible explanation is the behavior motivation. If an individual holds a egoistic motivation, his/her actions would not match his/her words. Conversely, if an individual holds a altruistic motivation, his/her behavior may consistent with his/her words. To help citizens "walk the talk," Litvine and Wustenhagen (2011) showed that providing information and communication can positively influence stakeholder actions in terms of achieving a green environment. Communication can reduce uncertainty or information asymmetry. Thus, communication would increase the possibility of altruism. However, our findings show that most stakeholders do not know how to get the requisite information about pollution prevention.

As well as the issue of consistent stakeholder perceptions, we also discovered cognitive conflicts between them. On the one hand, these findings show conflicts between local authorities and the market. The former takes the view that market-based regulation is the most important means to reduce air pollution. They emphasize that the market should be regulated (e.g., price and production). However, enterprise managers do not want to be regulated. They attribute air pollution to car exhausts and heating. On the other hand, our findings also show the conflicts between local authorities and social groups. The former group states that media exposure is the least important means reduce air pollution, while the latter group sees media exposure as the most important way of obtaining information to reduce pollution. Local governments are also reluctant to release air pollution information to the public.

In our opinion, there are a number of contributions our study could make to environmental policymaking. The first is that policymakers should consider the participation of stakeholders, simply because the stakeholders have cognitive differences on the causes of and solutions to air pollution. Those cognitive conflicts are useful to policymaking (Jehn, 1997). The second contribution is to consider which department should be responsible for the air pollution problem. In May 2010, the State Council of China issued the *Joint Prevention and Control of Air Pollution* (Zhang et al., 2016). This is the first comprehensive policy document aimed at improving air quality through government department cooperation. Local governments should weigh the air pollution matter seriously. In most Chinese cities, the environment department is responsible for environmental services. This system, however, does not work well. According to our study's conclusions, multiple-sector cooperation may be a better choice. The last contribution of our study is to consider which types of environment management tools are most effective. Our research finds that market regulation, media exposure, education and emission reduction attract a great deal of attention from stakeholders. However, the punishment tool is not seen as important by any group of stakeholders, which is inconsistent with existing policy instruments or previous studies. Existing policies and studies focus on intensifying penalties (Feng and Liao, 2016), but few of them discuss the importance of communication in policy-making and implementation. Environmental protection is a complex, wicked problem, with substantive, strategic and institutional uncertainties (Koppenjan and Klijn, 2004). These uncertainties can increase cognitive conflicts. Communication or negotiation can reduce these uncertainties. Communication can be defined as information exchange, which then increases transparency. Transparency in this case is the availability of information about one participant that allows other participants to monitor the performance of the first participant (Meijer, 2013). From this point of view, communication (or transparency) is an effective way to reduce cognitive conflicts.

Nevertheless, some limitations in this research do exist. The first limitation is the object of our study, which only has four categories. Some non-governmental environment organizations should be included in our future research. Moreover, due to time restrictions, our research samples only covered five cities in north of China. We also interviewed only 105 respondents. In a future study, we will make up for these inadequacies.

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

The author confirms being the sole contributor of this work and has approved it for publication.

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A Conceptual Framework for Collaborative Development of Intelligent Construction and Building Industrialization

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Digitalization drives the arrival of the era of intelligent construction, which greatly affects the development of construction industrialization. Due to the collaborative barriers between intelligent construction and building industrialization (ICBI), it is difficult for construction enterprises to participate in the actual engineering projects in this work. Achieving the collaborative development of ICBI has become a way to transform and upgrade the construction industry, and it has attracted more and more attention. However, the existing literature lacks consensus on the collaborative development of ICBI affecting the construction industry. In order to promote the theoretical research on the collaborative development of ICBI, this paper proposes a "mi" shaped conceptual framework so that readers can understand the operation law of ICBI collaboration and promote its healthy development. Therefore, based on the synergy theory, this paper extracts the contents of stakeholders' collaboration, industrial collaboration, structural collaboration, construction technology upgrading, factor endowment upgrading, innovation service upgrading, and construction process upgrading. These seven items are summarized into four dimensions: dual drive, resource supply, collaborative operation, and trust guarantee, which indicate the direction of ICBI collaborative development. The research results will help to realize the industrialization of new buildings and promote the sustainable development of the construction industry.

Keywords: digitization, intelligent construction, building industrialization, collaborative development, construction enterprises, dimensions, synergy

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1 INTRODUCTION

In recent years, digitization has brought an industrial revolution to the construction industry (Watson, 2011; Buchli et al., 2018; Tetik et al., 2019). Such digital technologies, including the digital twin, building information modelling (BIM), and the internet of things, have driven Construction 4.0 and brought the construction industry into an intelligent construction era (Craveiro et al., 2019; You and Feng, 2020). Intelligent construction has a significant impact on the development of the construction industry. For example, building a multi-stakeholder management and control platform can integrate smart factories with the internet of things and locate prefabricated components intelligently through digital collaborative design (Kozlovska et al., 2021; Turner et al., 2021; Yuan et al., 2021). Construction robotics play an important role in human-robot coordination and self-learning, making construction more efficient (Yan and Zhang, 2021). In particular, to promote intelligent construction in engineering construction, high-quality development requires the construction industry to take building industrialization as a carrier (Li et al., 2018). Intelligent construction is an innovative construction model that combines digitalization and engineering construction, which helps break through the bottleneck of information integration and interaction in prefabricated buildings (Wang et al., 2020; Wen, 2021). A priority for intelligent construction to assist in the development of construction industrialization.

According to China's commitment to carbon-peak and carbon-neutral at the United Nations General Assembly in 2020, energy conservation and emission reduction in construction are crucial contributors (Wong et al., 2013; Zhang et al., 2019; Li et al., 2020). The high-quality development in the construction industry has intensified the competition among construction enterprises, changing the industrial chain's traditional competition and cooperation mode. Construction enterprises urgently need to promote green and low-carbon development through the in-depth integration and innovation with intelligent construction technology, from the whole life cycle of building material production, construction, operation, and maintenance (Shi et al., 2019; Li et al., 2021). Relying on intelligent construction to carry out cross-disciplinary, cross-industry, and cross-department in-depth collaboration is also one integral approach for construction enterprises to enhance their independent scientific and technological innovation capabilities (Xue et al., 2018; Zhang et al., 2020). In the context of dual carbon, whether it responds to the call to promote mutual integration or actively seeks to improve its market competitiveness, the collaborative development of ICBI is imperative. However, such gaps in this work, including application scenarios and the management platform, have obstructed the healthy development of construction enterprises. Therefore, conceptual work is proposed for the collaborative development of ICBI to realize high-quality development in the construction industry. Three research questions were developed to shape this research:

RQ1. Which theories support or justify the collaborative development of ICBI within digitization?

RQ.2 What are the contributing paths to the effective collaborative development of ICBI in accelerating the transformation and upgrading of the construction industry?

RQ.3 What dimensions do the "mi"-shaped conceptual framework contribute to the effective collaboration of ICBI?

The remainder of this paper is organized as follows. **Section 2** reviews the research related to ICBI and synergy; **Section 3** constructs the "mi"-shaped conceptual framework associated with the collaborative development of ICBI; **Section 4** discusses the applicability of the conceptual framework in depth from four dimensions, and **Section 5** reports the conclusions.

2 LITERATURE REVIEW

2.1 Intelligent Construction and Building Industrialization

With intelligent construction in the engineering field, ICBI has been continuously improved for critical technologies such as engineering software, engineering internet of things, engineering machinery, and engineering big data (Liu et al., 2021). However, the collaborative development of ICBI is relatively slow. ICBI is an essential part of the fourth industrial revolution, and it did not show agglomeration development mode until 2017. Related literature research mainly focuses on digitization, cloud platform, and industrialization (Woodhead et al., 2018).

(1) As an advanced stage of digital construction, intelligent construction originates from the development of digital and intelligent technologies. It plays a vital role in standardized building, mechanized construction, and scientific organization and management (Rossi et al., 2019). ICBI improves the cost performance and reliability of the whole industry chain, which is a reliable methodology that guides construction to develop standardized design modules and component libraries (Bucchiarone et al., 2019).
(2) For fabricated construction industry chain and intelligent robotics, construction enterprises have established a BIM data management platform, which can realize the effective transmission and real-time sharing of BIM data in survey, design, production, construction, acceptance, and others (Edirisinghe, 2019). Such essential platforms, including the intelligent production platform for parts and components, the intelligent logistics platform for building materials, the intelligent installation and the intelligent park management service platform, and the building material centralized procurement platform, have solved the information flow integration problem in the construction industrialization supply chain and improved the intelligent construction degree (Ding et al., 2018).

(3) The deepen Industry 4.0 assists the stability of the collaborative development of ICBI, appearing the leading role of enterprises with advantages in intelligent construction (Kochovski and Stankovski, 2018). Project general contracting enterprises and whole-process engineering consulting enterprises have substantial impacts on improving the ability of intelligent construction solutions. For example, a multi-party collaborative intelligent construction work platform was established to strengthen collaborative work and gradually form an open industrial system that considers general engineering contracting enterprises the core (Zhou et al., 2018).

In short, scholars have conducted multi-angle and in-depth research on ICBI, focusing on the specific application and engineering practice in this work. Relevant theories, key technologies, and development systems have not yet been formed. Collaborative development is a hot topic and gradually becoming an essential research node related to ICBI. Intelligent construction is the basis for construction industrialization, and construction industrialization supports the development of intelligent construction. It is the key to realizing the collaborative development of ICBI.

2.2 Synergy Theory

Synergy theory started from Haken's work. It has previously been used to form a mode of action in which the matter, information, and energy in the system spontaneously generate an orderly organization through the transformation among variables (Haken, 2000). Haken believes that synergy is the main factor of the system beyond the fusion linkage produced by a single element. After that, synergy is considered a common goal: a network of self-motivated personnel to form a collective vision and exchange ideas, information, and working conditions through the network (Baldwin and von Hippel, 2011; Hartley et al., 2013). Tracing the evolution of synergy theory, it aims to expound the connotation from stakeholders' perspectives, action path, and operation process.

(1) Synergy is a non-linear organizational behavior that discusses stakeholders' complementary advantages, shared resources, and interaction among elements (Paulus et al., 2018; Anzola-Román et al., 2019). Through system integration, stakeholders promote organizational activities from disorder to order (Najafi-Tavani et al., 2018; Hong et al., 2019). Stakeholders usually do not act in isolation. They realize cross-field and cross-industry cooperation through multiple subjects, including "enterprise-enterprise," "enterprise-government," "enterprise-intermediary institution," and "enterprise-government-university-intermediary institution-financial institution-platform" (Feranita et al., 2017; Alford and Duan, 2018; Gao et al., 2019; Wang and Zhang, 2019; Zan et al., 2021). The cooperative or industrial alliance among construction enterprises, the knowledge innovation chain, and external innovation resources complicate collaborative activities.

(2) Synergy network is an essential carrier for stakeholders to carry out collaborative activities (Hadjimanolis, 1999). Synergy network has different structures, such as vertical collaboration, horizontal collaboration, and structural holes (Wang et al., 2014; Maietta, 2015). According to the formation of associated nodes by innovation stakeholders, it is found that there are significant differences in the impact of synergy networks on innovation performance, and vertical synergy is more significant than horizontal synergy (Zeng et al., 2020). The structural holes of enterprise synergy and knowledge networks are positive and negative in different situations. In reality, knowledge sharing is also an important way of collaborative development. Taking knowledge as the center, the collaborative open management and agglomeration effect among enterprises (Connell et al., 2014; Knoke et al., 2017). Collaboration among stakeholders begins with communication and cooperation, which will generate spillover information. It will bring spillover effects that have good or bad economic effects for the industry and even other industries. The transmission and digestion of information can promote technological innovation and achieve optimal benefits (Howard et al., 2016).

(3) Synergy activities have affected various factors, driving stakeholders to achieve sustainable development (Su et al., 2018). The organizational scale, the organizational object, and the organizational background are potential moderators that affect the achievement of collective goals (Vega-Jurado et al., 2008; West and Bogers, 2013; Dooley et al., 2016). Shorter technical and management knowledge distances are conducive to the collaboration of the whole process and improve collaboration performance (Schulze and Brojerdi, 2012). In-depth thinking on technological research, integration, and industrialization innovation plays an essential role in improving the competitiveness of stakeholders (Huizingh, 2011; Anzola-Román et al., 2019).

Overall, the concept of synergy theory revolves around groups and organizations. The existing literature lacks a comprehensive and systematic discussion, and the conceptual framework research needs to be increased. Under the integration pattern of the knowledge economy, enterprises have entered the management mode with complex people as the background. Enterprise benefits are more and more dependent on the collaborative operation. However, there are gaps in the research on construction enterprises under the guidance of synergy theory. Therefore, it is of great significance to construct a conceptual framework in architecture based on synergy theory, stakeholders' synergy, paths' synergy, and processes' synergy.

3 RESEARCH METHODS

3.1 Data Sources

Since the beginning of the 21st century, ICBI has gradually become the focus of academia, enterprises, and governments. In order to gain an in-depth understanding of the current status of ICBI in China, this paper mainly adopts two methods to obtain data resources.

On the one hand, the "Intelligent Construction and Building Industrialization" was searched in the China Social Science Index Core Database, with a period of 2001–2021, and a total of 120 valid documents were retrieved. Using CiteSpace for visual analysis, the co-occurrence graph, timeline graph, and time zone graph of domestic ICBI research keywords are obtained. Through an in-depth analysis of these maps, we can further explain the basic principles of China's ICBI collaborative framework construction.

On the other hand, the web crawler technology is used to automatically crawl a large amount of text information on the websites of the Ministry of Housing and Urban-Rural Development of China and the Ministry of Housing and Urban-Rural Development of various provinces and cities and

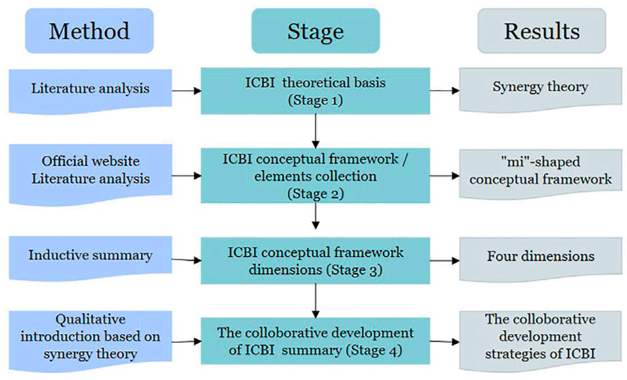

FIGURE 1 | Research flowchart.

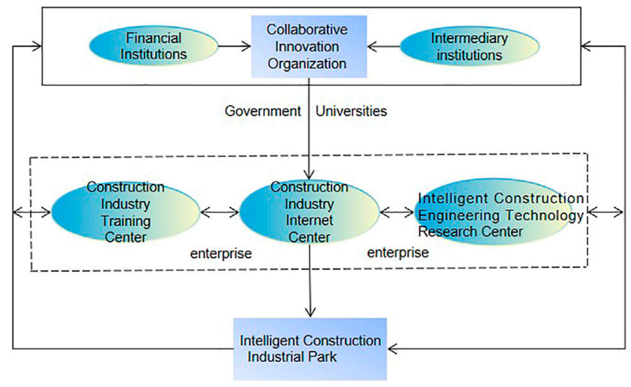

FIGURE 2 | Stakeholders' Collaboration in the collaborative development of ICBI.

conduct text analysis and advanced processing, keyword extraction, and word cloud analysis. Finally, the essential elements of the collaborative framework of ICBI are summarized.

3.2 Research Process

In China, the integration of ICBI is regarded as a new production method that promotes the flow of building data, improves the quality and efficiency of the entire industry chain, and maximizes the value of resources. Under the influence of the internal and external environment, construction enterprises can produce synergies that a single construction enterprise cannot achieve. Based on the synergy theory, this paper obtains the "mi"-shaped conceptual framework by analyzing the mechanism of the collaborative development of ICBI. The framework shows the complex relationship among the construction enterprises interacting, cooperating, and restricting each other. The research flowchart in this study is shown in **Figure 1**.

Firstly, based on the literature analysis method, the research status of ICBI and synergy theory are analyzed. This paper clarifies the research hot spots and directions of ICBI and points out the guiding significance of synergy theory to the sustainable development of construction enterprises. This work illustrates the critical role of synergy theory in the full text.

Secondly, according to literature analysis and web crawling results, this paper constructs a mi-shaped conceptual framework. The framework is obtained based on the ICBI synergistic development mechanism. Under the guidance of synergy theory, combined with the development practice of the construction industry, the discussion will be carried out from the direction of stakeholders' collaboration, industrial collaboration, structural collaboration, construction technology upgrading, factor endowment upgrading, and innovation service upgrading, and construction process upgrading.

Thirdly, this paper conducts an in-depth analysis of the conceptual framework of "mi"-shaped and summarizes the seven research contents into four dimensions from the perspective of synergy theory. Further in-depth analysis of the influence of each element in these dimensions on the collaborative development of ICBI will help identify the direction and improve the degree of synergy and innovation performance of ICBI.

Fourthly, a qualitative study is carried out to summarize this paper's research results, innovations, and future research directions.

4 CONCEPTUAL FRAMEWORK

4.1 Stakeholders' Collaboration

Generally speaking, there are many stakeholders in the collaborative development of ICBI. Specific chain-type technical and economic correlations are formed based on specific logical and space-time layout relationships. Due to the application of intelligent construction in engineering construction, the whole industry chain covers scientific research, design, production and processing, construction assembly, and operation, which can improve construction mechanization. In order to break through the innovation barriers of the entire industry chain, stakeholders require docking interaction and integration union. These behaviors are conducive to identifying and detecting unsafe behaviors in construction and promoting communication and cooperation among all parties involved in the project.

The design enterprises are committed to promoting full-professional collaboration, BIM cheerful design, and a standardized module library for BIM applications that cooperate with scientific research enterprises and decoration enterprises. Research institutions and development enterprises jointly establish a technology innovation alliance to research BIM underlying software and construction robotics. The construction enterprises continue to promote the inheritance and innovative application of new technologies in on-site construction links, such as distributing steel, processing steel, spraying, laying floor tiles, installing partition panels, and high-altitude welding, to achieve system integration and linkage development.

Construction enterprises have adopted a new digital and intelligent integrated development model to build many national-level prefabricated construction industry bases.

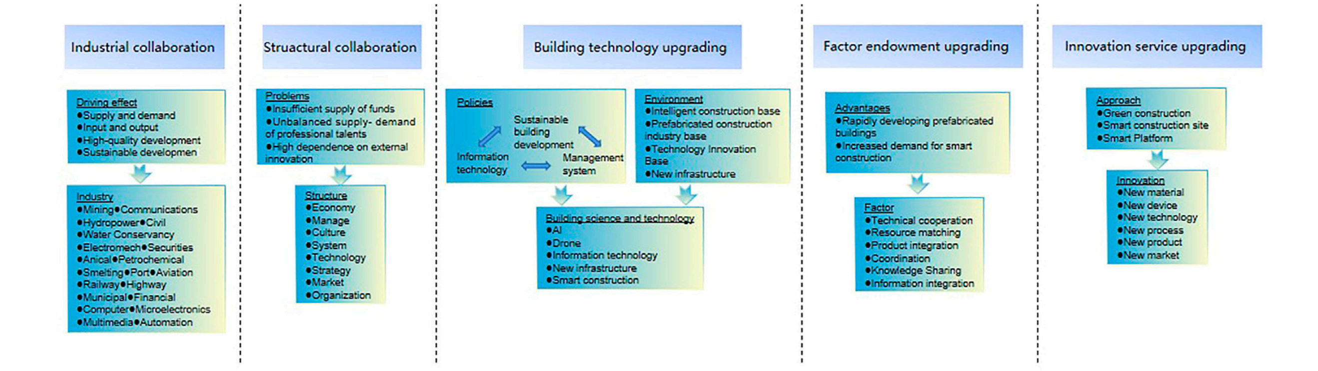

FIGURE 3 | Collaborative Paths in the collaborative development of ICBI.

Integrate the source of innovation of prefabricated construction enterprises with universities, form a collaborative organization network with intermediaries, and promote the industrialization development of new technologies and new products of prefabricated construction. The government and financial institutions are actively creating leading-level intelligent construction industrial parks, giving intelligent construction industrial parks a core position in the layout of modern construction industry clusters, including Construction Industry Training Center, Construction Industry Internet Center, and Intelligent Construction Engineering Technology Research Center. **Figure 2** shows the specific content of stakeholders' collaboration.

4.2 Collaborative Paths

The stakeholder network relationship is the fundamental driving force for collaborative activities. These relational networks are viewed as complex adaptive systems. Under the guidance of systematic methodology, there are interactions among and within systems. With the evolution of the network structure, **Figure 3** illustrates the collaborative paths in the collaborative development of ICBI, including industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, and innovative service upgrading.

4.2.1 Industrial Collaboration

The long industrial chain and the significant driving effect are the main characteristics of the collaborative development of ICBI. Therefore, its changes usually significantly impact other industries, driving multiple industries to seek development. From the perspective of supply and demand, large-scale and diversified buildings in society depend on the technology and services of intelligent construction. They cannot be separated from mining, communication, hydropower, water conservancy, petrochemical, and smelting. From the perspective of input and output, the growth rate of real estate investment in China has slowed down under the supply-side reform policy. The government work report pointed out that the proportion of real estate investment in GDP will continue to decline during the "14th Five-Year Plan" period. As an integral approach to stabilizing growth, the investment growth rate of construction enterprises in ICBI is expected to increase, further radiating ports, civil aviation, railways, municipalities, highways, and other industries. From the perspective of high-quality development, when construction companies adopt the general contracting model, they establish a multi-party collaborative intelligent construction work platform, which can, to a certain extent, clear up PPP projects for financing purposes and "pseudo" PPP projects packaged in disguised form. The proportion of projects that conform to the essential characteristics of PPP, green environmental protection, and people-benefiting has increased significantly, which is of great significance to the development of finance, securities, and other industries. From the perspective of sustainable development, construction enterprises are changing from cost-driven to innovation-driven. With the rapid penetration and diffusion of intelligent construction into building industrialization, construction companies are committed to using the Internet of Things technology to realize the online linkage of production equipment. Through promoting the practical experience of intelligent construction robotics in the pilot projects, the connection is gradually increased, such as computer, microelectronics, multimedia, automation, and other fields.

4.2.2 Structural Collaboration

Affected by the diversified development model of the construction industry, insufficient capital supply, imbalanced supply and demand of professional talents, and high dependence on external innovation have restricted the diversified and sustainable development of construction enterprises, including economy, management, culture, system, technology, strategy, market, and organization. First, the growth rate of total profits of China's construction enterprises has been declining since 2018 and has shown a downward trend in the past 5 years. Economic benefits reduce the enthusiasm of stakeholders in resource sharing and advantage integration, resulting in a shortage of funds for ICBI's coordinated development. It is urgent to establish a sound, intelligent construction, diversified investment system, and diversified financing model. Second, the proportion of personnel engaged in scientific activities in construction is relatively low compared with other industries during the same period. In addition, investment in scientific research innovation and new technologies is less than 1% of the total income for construction enterprises, and the supply and demand of intelligent construction talents are seriously unbalanced. Establishing a talent mechanism for the introduction, training, and development related to ICBI and cultivating new highly integrated talents, such as engineering construction + digitization, engineering construction + intelligence, engineering construction + information, are the support to promote the collaborative development of ICBI. Third, the core technology in China's construction enterprises is still highly dependent on foreign countries. More than 50% of the intelligent construction equipment needs to be imported. Critical technical problems need to be overcome urgently. It is necessary to develop prefabricated buildings vigorously, promote intelligent building technologies such as construction robots, intelligent factories, RFID, and QR codes, and realize the traceability of the whole process of quality responsibility. Stakeholders have established an advanced and applicable standard system for ICBI to strengthen BIM forward design and integration optimization. Also, it can promote the efficient sharing of various resources in the entire construction industry chain.

4.2.3 Building Technology Upgrading

Since 2016, the collaborative work of ICBI has been carried out in an orderly manner in the top-level design. China has introduced many policies to gather resources and strengthen the deep integration of information technology with the construction industry. Lean construction and intelligent construction are the primary means of building technology upgrading for construction enterprises, which help to comprehensively improve the quality, performance, and efficiency of engineering projects. In order to achieve the development goals of high efficiency, high quality, low consumption, and low emissions, intelligent construction and building industrialization application scenarios are encouraged to build, such as prefabricated building industry bases, intelligent construction bases, technology innovation centers, and critical laboratories. According to the 34 trillion new infrastructure plan jointly released by 13 provinces in China in 2020, the deep integration of digitization and intelligence associated with construction sites has provided opportunities for accelerating intelligent construction. One substantial contribution to the new infrastructure is that upgrading the traditional construction method can boost the modernization of China's construction industry into the fast lane. Under new infrastructure, construction enterprises play the main innovation body, focusing on innovative application scenarios, such as fabricated buildings and construction sites. Construction enterprises are committed to targeting cutting-edge international technologies, such as developing and applying construction robots and intelligent construction equipment, constructing industrial Internet platforms based on BIM digital technology, and establishing intelligent construction standard systems and evaluation systems. Through the continuous exploration of intelligent building technology, the contribution of scientific and technological progress to economic growth will be enhanced, and the sustainable and healthy development of the economy will be promoted.

4.2.4 Factor Endowment Upgrading

Based on information integration and knowledge sharing, construction enterprises gradually realize the organic synergy of ICBI, relying on the factor endowments upgrading. Such as technical cooperation, resource matching, product integration, and coordination have promoted joint research and demonstration applications for core technologies of intelligent construction, which help build an excellent industrial innovation ecology. On the one hand, it showed that the total area of newly started prefabricated buildings in China would be 630 million square meters in 2020, accounting for about 20.5% of the new construction area. Compared with the newly started prefabricated buildings in 2019, the total area of newly started prefabricated buildings has increased by 50%, and the integration of prefabricated steel structures is advancing rapidly. The development of prefabricated buildings is a significant change in the construction industry, conducive to promoting the deep integration of the construction industry and industrialization. The integrated application of the internet of things in intelligent construction sites guides information sharing. It establishes a prefabricated building development system that integrates the entire industrial chain from scientific research, design, production, construction, and assembly to operation.

On the other hand, the scale of China's artificial intelligence core industries accounted for more than 15% in 2017. Large public and commercial buildings' energy-saving needs have contributed to intelligent construction. Based on this, the market has cultivated many intelligent construction enterprises. They have realized the data sharing and effective transmission of the whole process and built the prefabricated construction industry chain with the support of the market. It helps to innovate and breakthrough core intelligent technologies, enabling construction enterprises to gain and maintain development advantages.

4.2.5 Innovation Service Upgrading

The certification application of new green building materials is considered an important strategy to help the green development in construction under double-carbon. To promote the application of new intelligent green building materials with good functions, construction enterprises focus on the innovative application of green construction to further promote a green energy-saving system. China's construction enterprises are leading in the world in intelligent construction, especially in applying intelligent construction methods in large and complex projects, such as construction robotics, intelligent building machines, and integrated intelligent construction equipment. The primary urban information model platform and the full-life-cycle project management platform associated with technological innovation, factory production, and intelligent applications have been established to apply the intelligent technology to the construction industrialization projects, such as digital component

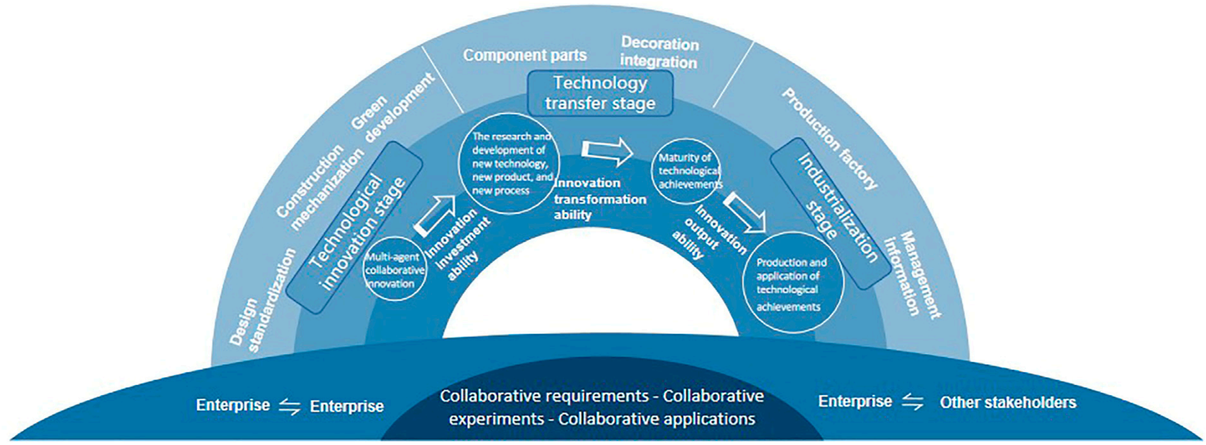

FIGURE 4 | The whole process in the collaborative development of ICBI.

factories, virtual construction, and installation, and on-site remote supervision. New technologies and products for intelligent buildings bring competitive advantages to construction companies and drive stakeholders to explore new markets actively. Construction enterprises gather various industrial resources, actively guide engineering projects to achieve innovative service upgrades, and promote the application of new materials, new equipment, new technologies, new processes, new products, and new markets.

4.3 Construction Process Upgrading

The collaborative development of ICBI is a dynamic process that consists of two chains. The internal chain is collaborative demand-collaborative experiment-collaborative application. The external chain is technological innovation-technology transfer-industrialization. **Figure 4** illustrates the collaborative effect between the internal chain and external chain. The collaborative objectives guide stakeholders to generate the demand for collaborative operation, then enter the technological innovation stage. New technologies have to undergo repeated trials from development to application to realize technology transfer with the joint efforts of stakeholders, thereby promoting the implementation of the results. The intelligence and industrialization level of the whole process in construction has been dramatically improved. A new generation of information technology and engineering construction technology is integrated through industry-university-research cooperation, guiding the transformation of scientific and technological achievements in three steps.

In the technological innovation stage, the bold design and integration optimization of BIM promotes one-click drawing of standardized design plans, establishes a standard component library, and realizes design standardization. The internet of things and intelligent technology ensure construction mechanization, promoting the online linkage of machinery, such as measurement robotics, innovative measurement tools, parts production robotics, construction robotics, and intelligent engineering equipment. Construction enterprises, universities, and scientific research institutions are conducive to accelerating the elimination of outdated equipment and technologies through the development of platforms, including integrated construction platforms and data management platforms, guiding green development.

In the technology transfer stage, the pilot application of intelligent construction was launched in several engineering projects to promote the smooth transformation of intelligent construction technology. Leading prefabricated construction enterprises help to realize the integrated development of decoration. The advantages of integration and cooperation are crucial to vigorously develop prefabricated buildings and enhancing the transformation capacity of intelligent construction technology.

In the industrialization stage, in the production of general components, supporting the production of building parts, and essential process production, prefabricated construction enterprises will increase the number of patents and expand the market share and scale of use of components through knowledge sharing, information integration, coordination, and cooperation. With the help of scientific management methods, the internet platforms in construction are built to realize a few or even factories without workers and gradually reduce the production costs of components and parts.

To sum up, the study proposes a "mi"-shaped conceptual framework for the collaborative development of ICBI. The findings of the descriptive analysis are summarized in **Figure 5**. The conceptual framework shows the complex relationship among stakeholders in the interaction, cooperation, and mutual restriction, clarifying the collaborative development path of ICBI. First, the diversified development of intelligent construction acts on industrial collaboration and forms a linkage development mechanism with multiple industries. Second, problems such as insufficient funds, unbalanced supply-demand of professional talents, and high dependence on external innovation promote the structural collaboration for construction enterprises from three aspects: driving force, innovation resources, and industrial chain

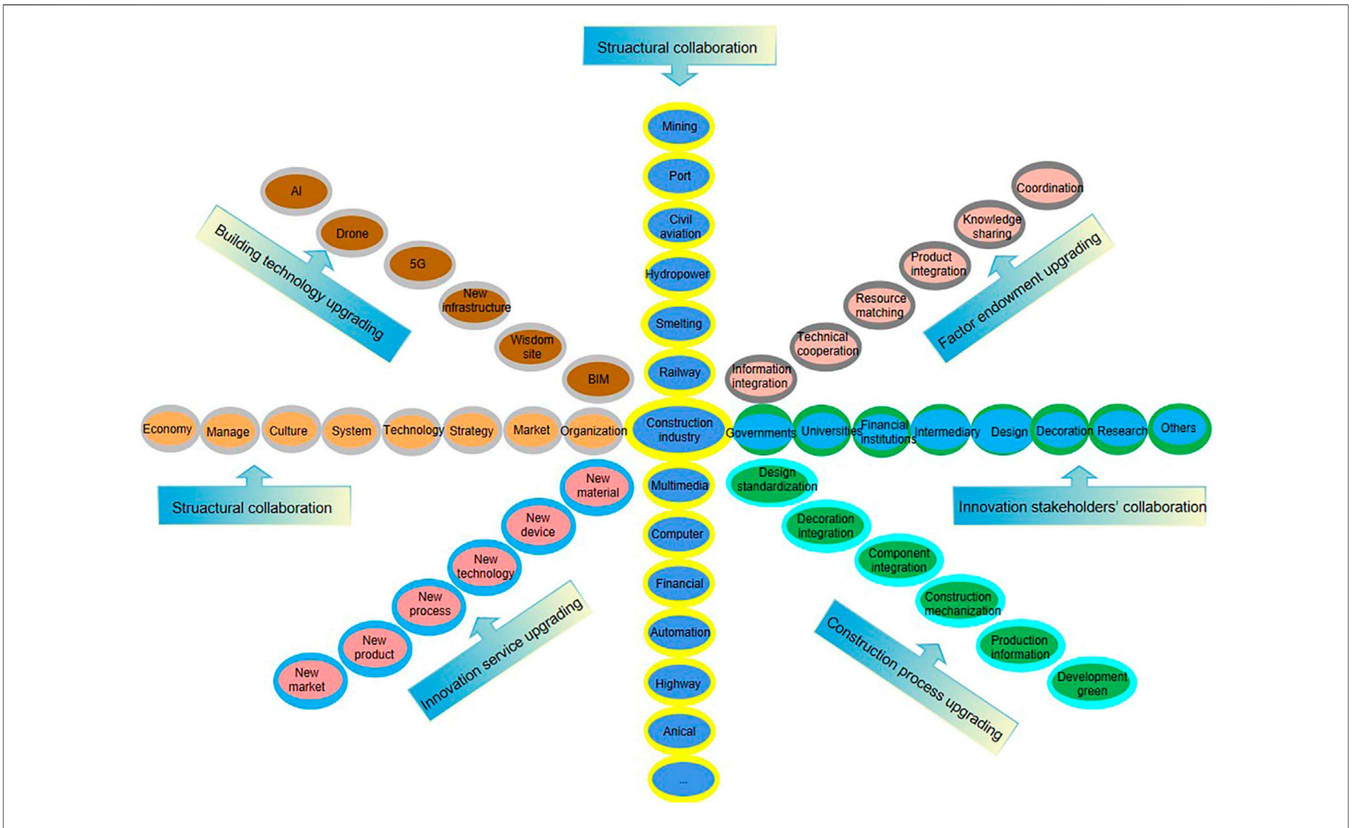

FIGURE 5 | "mi"-shaped conceptual framework in the collaborative development of ICBI.

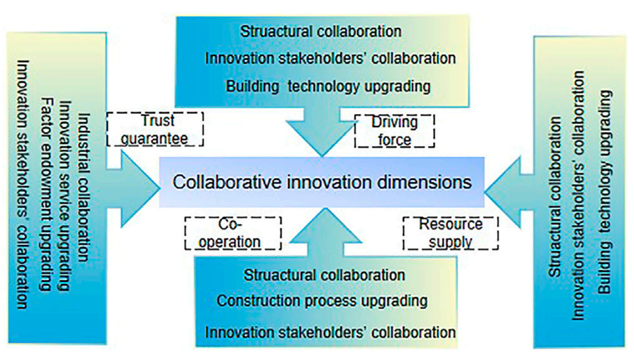

FIGURE 6 | Dimensions in the collaborative development of ICBI.

coordination. Third, the management system, the information technology, and the development of construction industrialization are deeply integrated to accomplish the construction technology upgrading for construction enterprises from the perspective of fabricated buildings and innovative construction sites. Fourth, the rapid development of prefabricated buildings and the increase in demand for intelligent construction will increase the factor of endowments upgrading. Fifth, intelligent construction promotes the construction industry's transformation to green, digital, and lean and ensures the innovative service upgrading smoothly in construction. Sixth, relying on standardization design, mechanization construction, green development, component integration, factory production, and scientific management, intelligent construction has achieved the construction process upgrading to industrialization in the whole process for the transformation of technological achievements.

5 DIMENSION ANALYSIS

Thus far, this study divides the conceptual framework of the "mi" shape into four dimensions, such as driving force, resource supply, collaborative operation, and trust guarantee, to further explore the collaborative development direction of ICBI, as shown in **Figure 6**.

1. In the process of mutual integration of valuable resources, the relationship between supply and demand has contributed to the collaborative development of ICBI, forming a synergistic driving force.
2. Resource supply focuses on innovation resources and agglomeration resources, which has built an integrated collaboration platform for intelligent construction enterprises and prefabricated construction enterprises.
3. Collaborative operation refers to injecting intangible assets into building industrialization, improving the construction

quality and efficiency of prefabricated buildings, and enabling multiple entities to achieve value increment.

It is mainly divided into whole-process collaboration and industrial chain collaboration. The key to the collaborative development of ICBI is trust among various subjects and a multi-dimensional guarantee. We discuss the four dimensions in more detail below.

5.1 Driving Force

There is differentiated demand for collaborative development of ICBI. Structural collaboration takes an interest in needs and innovation consciousness as internal driving forces to promote the sustainability of prefabricated buildings. The building technology upgrading expands the scale of collaborative competition among construction enterprises, affects the resource integration and information interaction for construction enterprises with universities, intermediaries, and financial institutions, and it drives the enthusiasm for intelligent construction as an external driving force (Guo and Li, 2022).

When prefabricated buildings show demand for new material, new technology, new process, new product, new equipment, and new market, construction enterprises urgently conduct intelligent technology research through coordinated development. It means to maintain existing profit levels and improve returns obtained interests. The experience center and education base of ICBI has increased society's attention to intelligent construction. The independent innovation awareness of construction enterprises has been increasingly strengthened (Skippari et al., 2017), which will improve the competitiveness among construction enterprises and guide the healthy development of the construction industry.

The government has formulated several development plans for ICBI and achieved lean management in construction by improving technology, finance, and talent policies. Universities have added ICBI-related majors, actively carried out universities-enterprise cooperation, and cultivated high-level talents. Intermediaries link universities, scientific research institutions, and enterprises to promote the optimal allocation and effective integration of various resources required in the transfer process of intelligent construction. The collaborative development of ICBI is a high-cost and long-term process, and market development is also hazardous. Construction enterprises play an essential role in the collaborative development of ICBI, which needs many funds. Financial institutions have vigorously carried out financial innovation through social funds, encouraged construction enterprises to participate in technology transfer actively, eased the financial pressure of construction enterprises in transformation, and improved transformation efficiency for scientific and technological achievements.

5.2 Resource Supply

To enable the collaborative development of ICBI and form a mutually beneficial pattern among stakeholders, such as government, universities, intermediaries, and financial institutions. Resource supply means investing resources to promote the development of construction enterprises towards technological innovation and resource agglomeration.

The supply of innovation resources includes talent, capital, and technology. The main body of talent supply is that construction enterprises and universities actively introduce outstanding talents in intelligent construction, and improve the skill evaluation system of construction practitioners from the perspective of ICBI. Focusing on the entire upstream and downstream industrial chain, such as digital design, intelligent production, and intelligent construction, connecting industrial parks with prefabricated construction enterprises and intelligent construction enterprises is an essential means to promote the establishment of prefabricated bases. Plot ratio incentives, appropriate relaxation of loan conditions, tax incentives following regulations, and services such as stock issuance and bond financing for construction industrialization enterprises will help build a sound capital financing mechanism.

Aggregated resources refer to the supply of macro policies, mainly from the government. Policy guidance, laws, and regulations play a role in the development process and risk prevention, conducive to optimizing the collaborative innovation structure for construction enterprises.

5.3 Collaborative Operation

The construction process upgrading drives the construction enterprises to conduct in-depth explorations of the whole collaborative innovation process. The technology innovation stage integrates design standardization, construction mechanization, and green development. The technology transfer stage focuses on the production of components and parts. Moreover, the industrialization stage implements production factories to produce general components, building parts, and key processes. Through the coordination of economy, management, culture, system, technology, strategy, market, and organization, construction enterprises with solid innovation and driving ability will be built from the perspective of the industrial chain.

Whole-process collaboration refers to how construction enterprises take necessary measures to improve their innovation input capability, transformation capability, and output capability at each stage of technological innovation, transformation, and industrialization (Persaud, 2005). Innovation investment refers to the research of modern construction industry products and intelligent construction technology by construction enterprises with the help of government technology management departments and scientific research funds. Innovation transformation is carried out in critical laboratories, pilot test bases, and industrial parks. Intermediary service agencies generally master the frontiers of technological development, which connect with universities and scientific research institutions to obtain cutting-edge scientific knowledge in technology. Construction enterprises take the industrialization of technological innovation achievements as the core and provide relatively mature technology applications for the technological development of construction enterprises. It contributes to increased competitiveness and economic benefits for stakeholders.

Industrial chain collaboration includes four aspects: capital chain, value chain, technology chain, and space chain. According to the advantages of construction enterprises, stakeholders provide whole-process financial support for new products, new technologies, and new processes and carry out in-depth cooperation in bank loans and equity transfers. Construction enterprises are adapting to the requirements of new construction industrialized production methods, and stakeholders continue to realize their own value-added. It is difficult for an enterprise to build a complete engineering project alone. Furthermore, a project needs to be jointly undertaken by several construction enterprises that master core technologies. Few enterprises can master all advanced technologies. Even leading enterprises need to coordinate with the upstream and downstream to improve their innovation capabilities. Construction enterprises in different regions are distributed and developed unevenly, which need to combine the actual development of the regional economy, society, and environment to build a chain of cooperation, complementary advantages, and joint development.

5.4 Trust Guarantee

A trust guarantee aims to enhance the trust among stakeholders and ensure members' enthusiasm to cooperate through incentive measures.

Factor endowments upgrading takes multiple factors as the core and relies on the trust mechanism to promote technical cooperation, resource matching, product integration, and coordination among construction enterprises. It helps to drive knowledge sharing and information integration among construction enterprises to solve the market competition problems. Intelligent construction promotes the digital transformation of the construction industry and brings together the strategic layout of "Internet + construction, finance + construction, investment + construction," guarantees the scientific nature of risk-sharing and income distribution with innovative service upgrading, and promotes the development of new materials, new equipment, new technologies, new process, new products, new market.

Trust is the foundation for the collaborative innovation operation of construction enterprises. Knowledge sharing, information integration, and other behaviors will help construction enterprises increase sunk costs and benefits (Wu et al., 2022). Knowledge sharing means that stakeholders promote the collaborative development of construction enterprises through knowledge diffusion among employees to achieve common goals. The primary way is to organize staff training and learn advanced scientific knowledge and construction technology from each other. Information integration invests talents, technology, and capital into cooperative innovation projects to form unified standards and reach basic cooperation consensus. Based on ensuring the trust of stakeholders, it can achieve a win-win or multi-win situation for stakeholders, thereby increasing the benefits of cooperation.

The dual incentive strategy of income distribution and risk sharing provides a fundamental guarantee for the operation of ICBI. Generally speaking, the expected benefits of transforming scientific and technological achievements are relatively high. Not only do construction enterprises gain industrialization profits, but participants such as universities and intermediaries that provide scientific research and transformation services for technology landing should also gain certain benefits. It involves issues such as valuation, share conversion, and financing. In parallel, risk and return are positively correlated, and the higher the expected return, the greater the potential risk. The risk factor for the collaborative development of ICBI is relatively significant.

The dimensions of the driving force, resource supply, collaborative operation, and trust guarantee cannot be studied in isolation. The collaborative development of ICBI is a composite system. In order to achieve the synergistic goal, **Figure 7** shows that there is a specific relationship between the four dimensions. These connections coordinate system elements to impact other elements or the whole to play better a synergistic effect, namely positive and negative loops.

The positive loop starts with the collaborative operation and develops technological innovation through whole-process collaboration and industrial chain collaboration. After the transformation of scientific and technological achievements, it realizes industrialized development, obtains economic benefits, increases the internal and external driving forces of collaborative innovation, promotes resource supply capacity, and stimulates the enthusiasm of ICBI, then acts on the dimension of collaborative operation. The positive loop is a collaborative operation—industrialization—driving force—resource supply—trust guarantee—collaborative operation.

The negative loop starts with collaborative resistance, which is a factor that hinders synergy in the collaborative process of ICBI. It may be caused by high coordination costs, invalid incentives, resource shortages, and innovation hindrance. By weakening the collaborative operation and reducing the transformation efficiency of scientific and technological achievements, the industrialization ability and dual driving ability are insufficient, resulting in tight resource supply and a low trust guarantee effect. This cycle will increase the collaborative resistance. The negative loop is collaborative resistance—collaborative operation—industrialization—driving force—resource supply—trust guarantee—collaborative resistance.

6 DISCUSSIONS

Collaborative development is a hot topic in the research of ICBI, and many stakeholders' behavior has been widely discussed around the world. Nevertheless, there is no theoretical framework to tell us how ICBI collaborative development explicitly. The primary purpose of the current research is to propose a "mi"-shaped conceptual framework to promote the collaborative development of ICBI through multi-path collaboration based on synergy theory. This paper analyzes the mechanism for effective implementation of ICBI on construction projects. In the mechanism, seven paths were studied, summarized into four dimensions. This study was applied to respond to three questions. The first asks: Which theories support

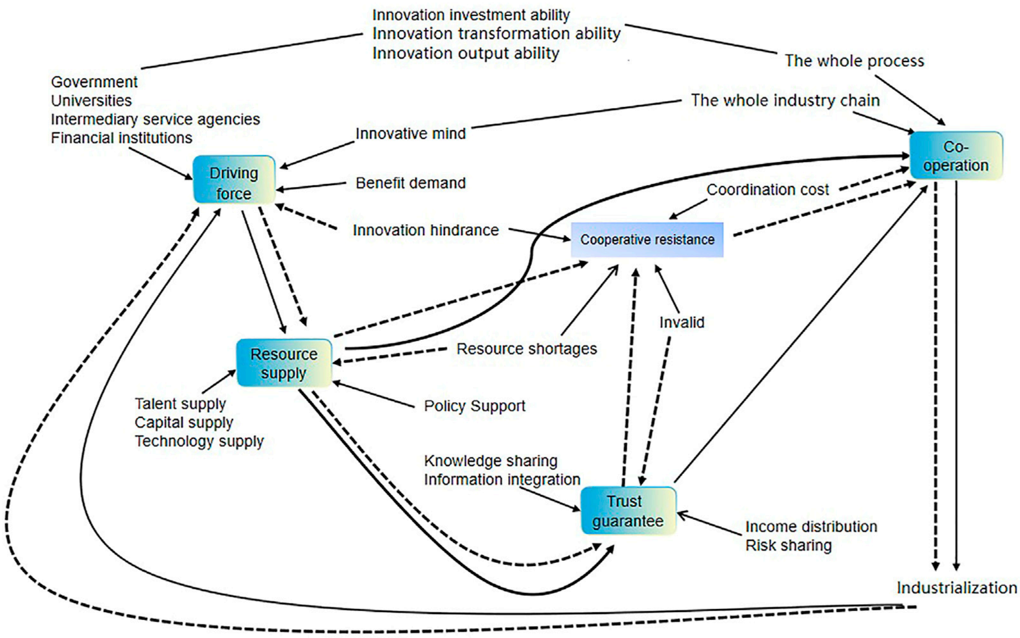

FIGURE 7 | The positive loop and negative loop in the collaborative development of ICBI.

or justify the collaborative development of ICBI within digitization? The answer, which is presented in **Section 2**, provides the foundation for the theoretical support. The second asks: What are the contributing paths to the effective collaborative development of ICBI in accelerating the transformation and upgrading of the construction industry? **Section 3** and **Section 4** explain the seven paths. The third asks: What dimensions does the "mi"-shaped conceptual framework contribute to the effective collaboration of ICBI? The answer is presented in **Section 5** to guide the direction for the collaborative development of ICBI. This paper has three principal theoretical contributions.

First, we have carefully reviewed the literature on ICBI and collaborative development. Research focuses on stakeholders, action paths, and operation processes. Theoretical research and practical discussion on the development of ICBI and other aspects are of great significance, which will help improve the construction industry's labor productivity, speed up the construction process, reduce the engineering cost, and improve the quality of the engineering project.

Next, combined with the development status of China's construction industry, a "mi"-shaped conceptual framework for the collaborative development of ICBI was established. The framework clarifies that stakeholders' collaboration, industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, innovative service upgrading, and construction process upgrading are the fundamental support for the collaborative development of ICBI. It explains the operating rules and principles for the interconnection of various elements under certain environmental conditions, which have essential theoretical significance.

Finally, to further explore the potential value of the conceptual framework and understand how to improve the level of ICBI, it is crucial to explore the four dimensions of the driving force, resource supply, collaborative operation, and trust guarantee, which are helpful to guide the development of ICBI.

7 CONCLUSION

This paper adopts synergy theory, applying it to the collaborative development of ICBI. It advocates for the development status of China's construction industry to consider stakeholders' collaboration, industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, innovative service upgrading, and construction process upgrading. Moreover, it proposes the potential value under four dimensions to improve the innovative performance of construction enterprises. In this regard, the "mi"-shaped conceptual framework could serve as a routine for construction enterprises to mitigate risks associated with the collaborative development of ICBI. There are three optional avenues to be explored in the future.

First, this study conducts a preliminary analysis of the stakeholders in the collaborative development of ICBI. It is necessary to conduct detailed research on certain two types. A "government-construction enterprise" decision analysis can be performed assuming limited rationality in future research. The evolution game model for "government and construction enterprise" is constructed to analyze both sides' evolution and stability strategy in collaborative innovation. Based on this, the study should change the simulation parameters to determine the stable equilibrium of evolution and propose countermeasures and suggestions for the collaborative development of ICBI.

Second, this framework is preliminary based on a literature review and status analysis. More empirical studies should be conducted in the future to develop it further. For example, the study will analyze the macro environment, existing problems, and development trends of the collaborative development of ICBI in different regions. Through data processing and result analysis, the applicability of this research framework should be verified. At the same time, it is also possible to provide a theoretical reference for the collaborative development of ICBI.

Third, the collaborative development of ICBI is a complex system. According to the positive loop and negative loop among various dimensions, the process and results for the collaborative development of ICBI can be further measured. 1) Several sequences and sub-sequence parameters are set up to build the synergy and innovation performance index system. 2) The synergy and innovation performance indicators are determined according to the entropy weight method. 3) Redefine the concept of the collaborative development of ICBI, and build a subsystem order model and an overall system synergy model. 4) According to the synergy and innovation performance of the collaborative development system of ICBI, the collaborative evaluation grades are divided to provide a method for measuring the collaborative development level of regional ICBI.

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

All authors contributed to the study's conception and design. LL performed material preparation and conceptualization; ZG wrote the first draft of the manuscript, and all authors commented on all versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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The relationship between firms' corporate social performance and green technology innovation: The moderating role of slack resources[1]

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This study explores the relationship between firms' corporate social responsibility (CSR) and their "green" technology innovation in the context of a developing country with a high level of economic growth (China). Using data from listed companies, green patent authorization data from the State Intellectual Property Office, and social responsibility rating data from Rankin's CSR Ratings of China from 2009 to 2017, we find that a higher CSR rating is highly positively correlated to green technology innovation as measured by number of green patents granted. Results indicated that corporate social performance plays a contributory role in green technology innovation. We also find that unabsorbed slack resources enhance the positive relationship between CSR rating and the number of green technology patents.

KEYWORDS

corporate social responsibility, green technology innovation, slack resources, moderating effect, green patent

1 Introduction

After a long period of rapid economic growth, China now faces severe challenges in ecological environment protection. According to the Ministry of Ecology and Environment, global warming has exacerbated the warming and acidification of China's surrounding ocean and caused ecological risks, such as sea level rise, tsunamis, and alien species invasion, that seriously threaten the safety and livelihoods of people in the China's coastal zone[2].

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2 Source: http://www.mee.gov.cn/ywdt/spxw/202108/t20210827_860765.shtml.

The question of how to achieve "green" development has become one of great concern to China in recent years, guided by the Chinese government's new focus on innovative, coordinated, green, open, and shared development[3]; on the philosophy that "green mountains are gold mountains"[4]; and on carbon peak and neutrality targets[5]. Green technology innovation is seen as an important way for China to achieve its "two Carbon" goal of coordinated economic and environmental development. With the implementation of a growing number of environmental regulations and the development of low-carbon technologies, many Chinese firms have committed themselves to the production of green products both to improve their competitiveness and to reduce carbon emissions.

Research has shown that by actively considering the interests of multiple (and possibly indirect) stakeholders, such as society and the environment, and by practicing corporate social responsibility (corporate social responsibility is abbreviated as CSR), firms can not only improve their own economic performance (Flammer, 2015) but can also promote the green development of society (Boulouta and Pitelis, 2014). Therefore, society may expect firms to assume more social responsibility and to help alleviate environmental pressure through green innovation, in China in particular (Zeng et al., 2020).

Studies have shown that there is an association between CSR and corporate innovation. There is a substantial body of research on CSR and technology innovation performance, and their economic effects (Martinez-Conesa et al., 2017; Ko et al., 2020). Some authors have found that many firms are able to access new markets and in so doing introduce outside knowledge that can promote increased levels of technological innovation (Piotr and Dawid, 2010; Bocquet et al., 2013; Bocquet et al., 2017). However, there are also studies showing that the CSR increases operating costs, affecting their research and development (R&D) inputs. Thus, CSR may have a negative effect on technological innovation performance (Gallego-Álvarez et al., 2011).

Luo and Du (2015) found that by strengthening the knowledge exchange between firms and external stakeholders, involvement in social responsibility plays a role in improving the performance of firm technology innovation. Similarly, Zhou et al. (2020) argued that by improving employees' work enthusiasm and strengthening cooperation with suppliers, CSR can increase levels of firm technology innovation. In a related paper Martinez-Conesa et al. (2017) noted that fulfilling social responsibility can enhance firms' innovation abilities, which is an important intermediary variable by which social responsibility can improve the financial performance of firms.

Different from traditional technology innovation, green technology innovation aims to achieve coordinated economic, resource, and environmental development by using new concepts and new technologies to reduce energy consumption and environmental pollution and obtain economic benefits. Most existing research focuses on the economic benefits of technology innovation, and studies on how CSR influences green innovation are scarce by comparison. Kraus et al. (2020) pointed out that firms engaged in CSR tend to pay more attention to green development strategies and as a result enjoy higher levels of green innovation. Likewise, Chang (2015) emphasized that in firms that proactively engage in social responsibility practices, high priority is given to the cultivation of green organizational culture, and more resources tend to be allocated for green innovative activities. From the perspectives of green identity and green organizational culture, current studies tend to view green innovation as a means practice CSR, and CSR practices promote firms' performance in green technology innovation (Kraus et al., 2020; AAchi et al., 2022).

Although existing research on CSR is abundant, there are still gaps to be explored. First, most research investigates the relationship between CSR and green technology innovation based on developed countries; only a few, studies have attended to the case of developing countries. According to Sharma (2019) developed countries have stronger environment protection consciousness and social responsibility than developing countries due to different economic development levels and cultures (Sharma, 2019). However, green technology innovation has recently become a more pressing concern in developing countries, especially for China, and the question of whether the CSR-green technology innovation relationship for North America and Western Europe also holds for developing countries deserves closer study (AAchi et al., 2022). Many developing countries are plagued by weak institutions, underdeveloped capital markets, weak contract enforcement, lack of business freedom, and weak legal systems and property rights (Ghoul et al., 2017; Ioannou and Serafeim, 2012; Lanis and Richardson, 2015).

Second, the question of what is the moderating role of firm slack resources between CSR and green technology innovation in weak institutional settings remains unanswered. Resource dependence theory posits that the survival and development of firms are restricted by resources (Hillman et al., 2009). With both social responsibility and green technology innovation, firms must integrate and reconfigure resources. Drawing upon concepts from slack theory from Singh (1986), slack resources can be classified into two types. One is unabsorbed slack resources (resources that are temporarily idle to prepare for new goals), and the other is absorbed slack resources (resources that are intentionally invested to achieve specific goals). We may therefore reasonably ask: What role do

3 Source: https://news.12371.cn/2015/10/29/ARTI1446118588896178.shtml.

4 Source: http://cpc.people.com.cn/GB/67481/412700/.

5 Source: http://www.gov.cn/xinwen/2021-04/22/content_5601515.htm.

slack resources plays and what effect differences between two types of slack resources. If we ignore the regulation of firm resources (Yuan and Cao, 2022) and focus on firms' green willingness or cultural aspects alone, we might not fully understand the relationship between the performance of CSR and green technology innovation. Furthermore, due to data availability issues, more studies have focused on the overall level of green innovation (AAchi et al., 2022) than the quantity or quality of green innovation. To fill this research gap, this study examines how CSR affects both the quantity and quality of green technology innovation and examines the moderating role of the above two types of slack resources in China specifically.

To help us with this examination, we employ green patent authorization data from the State Intellectual Property Office, social responsibility rating data from Rankin's CSR Ratings (RKS), and the data of Chinese A-share listed companies from 2009 to 2017. We find that firms with better performance in practicing social responsibility have higher numbers of green patents authorized. Furthermore, we find that the greater a firm's unabsorbed slack resources, the more positively CSR correlates to its green technology innovation.

The contributions of this study to the literature are twofold. First, by investigating innovation quality and the moderating effect of slack resources, this study deepens the understanding of the relationship between CSR and green technology innovation. Whereas existing studies have highlighted the role of firms' green innovation willingness (AAchi et al., 2022) and green technology innovation as a complex intellectual activity depending on the relevant resources of firms, this study finds that unabsorbed slack resources positively moderate the relationship between CSR and green technology innovation. Second, this study provides empirical evidence from a transitional developing country that CSR does in fact have an impact on green technology innovation. There are many differences for CSR and green technology innovation (green technology innovation is abbreviated as GTI) differences between developed and developing countries. Most explorations of the relationship between CSR and green technology innovation so far has concentrated on developed economies such as the United States or those in Europe, but there is scant research on developing countries such as China. Many developing countries face more severe environmental problems than developed countries, and their firms tend to have lower awareness of CSR practices.

We also note that Kawai et al., 2018 explored the relationship between CSR and green technology innovation for China's listed companies and the moderating effect of corporate social capital and the regulation of incentives on executives. By contrast, again, this study examines the moderating effect of firm slack resources and the quality of green technology innovation, drawing conclusions that enhance our understanding of the relationship between CSR and green technology innovation. The rest of this paper is organized as follows. Section 2 presents our theoretical analysis and research hypotheses. Section 3 describes the research design. The empirical results and analysis are presented in Section 4, and Section 5 concludes.

2 Theoretical analysis and research hypotheses

2.1 Corporate social responsibility and green technology innovation

Green technology innovation requires support from a wide range of external resources as it is a more complex intellectual activity than traditional technology innovation that necessarily involves the creation, integration, and diffusion of knowledge in different technical fields[6] within an organization. It typically has the characteristics of dynamic and diverse content, a highly complex R&D process, and high levels of uncertainty (Peng et al., 2014). These features mean that green technology innovation cannot be effectively carried out by relying merely on previous technical experience or knowledge in only a single technical field (Yuan and Cao, 2022). To this end, high amounts of CSR participation can strengthen the ties between a firm and external stakeholders (Cheng et al., 2014), help a firm obtain the recognition and support of these stakeholders (Chang, 2015), and attract a wider range of resources for green technology innovation.

By forging a better relationship with external stakeholders and lowering the uncertainty of external investment, high amounts of CSR participation can help companies acquire needed external resources, including technical know-how, highly skilled workers, and outside financing. For example, firms can attract capital resources from investors and creditors (Zhang et al., 2022a; Martin and Moser, 2016); human resources in the form of excellent employees (Wiggenhorn et al., 2016); market resources, such as customers and suppliers (Flammer, 2018); public environmental and institutional resources from the government and society; and technological information from universities and research institutions. However, in the era of increasingly strong demand for environmental protection, firms with "good" CSR performance cannot afford to overlook their environmental responsibility (Meng et al., 2013) and are more likely to adopt environment-oriented innovative behaviors proactively (AAchi et al., 2022). As a result, these firms invest both internal and external resources in a complementary fashion in order to promote green technology innovation. Accordingly, we propose the following hypothesis.

6 Examples of these technical fields include green product design, manufacturing processes, circular production, sewage treatment, and energy saving.

H1: Good CSR performance can promote a firm's output of green technology innovation.

2.2 The moderating role of absorbed slack and unabsorbed slack

Slack resources can be divided into absorbed slack resources (abbreviated as A-slack) and unabsorbed slack resources (abbreviated as U-slack). The unabsorbed slack resources of a firm are those resources possessed by the firm that have the potential to be developed and are able to support firm wide innovation. Firms can rapidly convert U-slack resources into those needed for all aspects of innovation activities. Absorbed slack resources, however, are difficult to reuse inside a firm once they have been put to use for specific projects.

Corporate social responsibility strategies and green technology innovation have a competitive relationship. Since both compete for firm resources, utilizing U-slack resources as either a basis for the initiation of corporate green innovation activities or as a buffer for environmental changes can positively affect corporate innovation activities. A firm can theoretically rapidly transform U-slack resources into sources for innovation activities when faced with new opportunities for market development. Although CSR is a strategic innovation rather than a technology innovation, both of these types of innovation require corporate resources.

Firms' U-slacks resources can be readily reconfigured to new targets and thus may exert a positive moderating effect on a firm's CSR-GTI relationship. The concept of U-slack[7] resources reflects the financing and investment capacities that firms can develop and utilize in the long term (Herold et al., 2006). After integrating green technology innovation knowledge and resources, a firm needs to consume additional learning costs to identify and absorb external knowledge and resources for green technology innovation, however, and here flexible U-slack resources can provide long-term support. They can improve the efficiency and capacity for firms to manage external knowledge and resources, deliver the specific knowledge and resources needed for green technology innovation, and boost the success rate of green technology innovation as well (Lee, 2009). In contrast, A-slack representatives are difficult to repurpose. In light of this we propose the following pair of hypotheses.

H2: U-slack resources positively moderate the positive relationship of CSR performance with green technology innovation.

H3: A-slack resources have no significant positive moderating effect on the relationship between CSR performance and green technology innovation.

7 U-slack resources include idle resources such as reserve funds, profit retention, and unused capacity, among others, and are flexible and easy to redeploy.

3 Research design

3.1 Data sources and sample selection

This study selected Chinese listed firms from the RKS index from 2009 to 2017 as a sample of relevant firms. Data on CSR ratings were collected from Rankin's CSR Ratings (RKS), the leading independent CSR-rating entity in China (Chen and Wan, 2020). Green technology innovation data were obtained from the website of the State Intellectual Property Office through python crawling, referencing the World Intellectual Property Organization (WIPO) IPC Green Inventory to identify green patents authorized (Xing et al., 2021). Data of all moderating and control variables were collected from the WIND database provided by Shanghai Wind Information Co., Ltd., and the CSMAR database provided by Shenzhen GTA Education Tech. (Bao et al., 2017). Our final sample was obtained by excluding the following categories: 1) firms in the financial or insurance industries; 2) companies that had not released a CSR report; 3) ST (special treatment) and *ST (delisting risk warning) companies with abnormal financial data; 4) samples with key missing data, such as firm's total number of employees. After applying these rules, we were left a total of 2,734 valid firms. Finally, we winsorized the continuous variables of firm characteristics using a 5% threshold for both tails to avoid possible estimation errors caused by outliers.

Drawing on Herold et al. (2006) and Peng et al. (2010), we measured slack resources by dividing current assets by total assets, and we classified slack resources into A-slack and U-slack. A-slack resources represent short-term solvency, (investment) financing capacity, and reflect the size of slack resources that the firm can directly utilize or transform in the short term. Higher A-slack means more "short-term idle" or "potential" resources that the firm has not fully utilized and more "short-term free" resources that can be used to support process or product innovation activities. By contrast, U-slack resources represent long-term solvency, liabilities (financing) and investment capacity of the firm, and reflect the financing and investment capacities that it can develop and utilize.

3.2 Model construction and variables

3.2.1 Model construction

We constructed the following model to test the impact of CSR on green technology innovation as well as the moderating role of firm slack resources.

$$Patent = \alpha_0 + \alpha_1 CSR_{i,t} + \sum \beta_i Control_{i,t} + \gamma Industry_i + \delta Year_t + \varepsilon \tag{1}$$

TABLE 1 Variable definitions.

Variable type	Variable name	Definition	Calculation
Dependent variables	GIt+1	Number of green patents authorized	Number of green patents authorized in period t + 1 (sum of invention patents and utility model patents)
	GIIt+1	Number of green invention patents authorized	Number of green invention patents authorized in period t + 1 divided by the number of green patents authorized in the same period
Independent variables	CSRt	CSR	Rankin's CSR Ratings
Control variables	Rdt	R&D investment	R&D funds divide total assets
	Debtst	Debt ratio	Total liabilities divided by total assets
	LnNstafft	Firm scale	Natural logarithm of total number of employees of listed companies
	Tonbinqt	Tobin's Q ratio	Market value divided by total assets
	Soet	Firm ownership	1 for SOEs, 0 otherwise
	LnAget	Firm age	Natural logarithm of the age of the listed company
Moderating variables	A_Slackt	Absorbed slack resources	Current assets divided by current liabilities
	U_Slackt	Unabsorbed slack resources	Owner's equity divided by total liabilities

$$Patent = \alpha_0 + \alpha_1 CSR_{i,t} + \alpha_2 Slack\ Resoures\ Variable + \sum \beta_i Control_{i,t} + \gamma Industry_i + \delta Year_t + \varepsilon \quad (2)$$

and $$Patent = \alpha_0 + \alpha_1 CSR_{i,t} + \alpha_2 Slack\ Resoures\ Variable + \alpha_2 \{Slack\ Resoures\ Variable\} * CSR_{i,t} + \sum \beta_i Control_{i,t} + \gamma Industry_i + \delta Year_t + \varepsilon \quad (3)$$

where *Patent* represents GI or GII in different situation (variable definitions are given in Table 1); *CSR* denotes the CSR performance score; *Control* represents the control variables; *Industry* stands for industrial variables; *Year* denotes the year variable; ε is the error term for each equation (abusing notation), assumed to be distributed (i.i.d. Normal with mean 0 and variance sigma 1); *A_Slack* represents firm absorbed slack resources; *U_Slack* represents firm unabsorbed slack resources; *ASla*csr* is the interaction term of centralized *CSR* and *A_Slack*; and *USla*csr* is the interaction term of decentralized *CSR* and *U_Slack*. In the data on green patents authorized, the dependent variable consists of "merging data" that has a left-truncated distribution, referring to (Chen et al., 2017). Hence we adopt the Tobit two-stage IV method for this regression.

Research on green innovation began in the 1990s and primarily focuses on green technology innovation specifically (Qi et al., 2018). Whether a technology is "green" is determined by a general heuristic rubric that considers technologies, processes, and products that lead to reduced pollution, less raw material use, or lower energy consumption. Generally, the existing literature measures firms' green technology innovation by questionnaire scoring or by R&D investment per unit of energy consumption, among others methods (Wang et al., 2021). However, such methods suffer from the problem of high subjectivity. To overcome this defect, we instead use the number of green patents authorized to measure firms' performance in green technology innovation as this is a more objective measure that can be quantified and also has the benefit of a large available sample of data.

In 2010, the WIPO published the *IPC Green Inventory*, which classified green patents into seven categories following the United Nations Framework Convention on Climate Change: transportation, waste management, energy conservation, alternative energy production, administrative mediation or design aspects, agriculture or forestry, and nuclear power generation, and we use these categories to count firm green patents authorized each year. Whereas Chinese patent law divides patents into invention patents, utility model patents, and design patents, the *IPC Green Inventory* includes only invention patents and utility model patents. For this reason, the green patents authorized in this study include the total amount of green invention patents and green utility model patents. In order to take green patents' sometimes processing times from the beginning of R&D to full patent authorization into consideration, we lag all proxy variables for green technology innovation by one period.

In the existing literature, RKS has been widely used to measure firms' CSR performance (McGuinness et al., 2017; Wang et al., 2018), and the higher the rating score means the better the firm's CSR performance. For mediating variables, we

TABLE 2 Descriptive statistics.

Variable	Definition	Sample size	Mean	SD	Minimum	Maximum
GI	Green patents authorized	2734	5.51	22.78	0	442
GII	Green invention patents authorized	2734	3.78	18.26	0	398
CSR	CSR	2734	38.10	11.85	14.15	87.95
Rd	R&D investment	2734	2.82	4.15	0	48.15
Debts	Debt ratio	2734	0.46	0.19	0.01	1.34
LnNstaff	Enterprise scale	2734	7.46	1.34	4.02	12.51
Tonbinq	Tobin's Q ratio	2734	1.80	1.60	0.09	14.71
Soe	Enterprise ownership	2734	0.56	0.49	0	1
LnAge	Enterprise age	2734	2.66	0.37	0.69	3.63
A_Slack	Absorbed slack resource	2734	2.00	2.41	0.09	51.13
U_Slack	Unabsorbed slack resource	2734	1.90	2.83	−0.25	62.45

TABLE 3 Correlation coefficient matrix.

	GI	GII	CSR	Rd	Debts	Tobinq	LnAge	LnNstaff	Soe
GI	1								
GII	0.963***	1							
CSR	0.146***	0.119***	1						
Rd	0.071***	0.087***	0.034*	1					
Debts	0.069***	0.054***	0.094***	−0.263***	1				
Tobinq	−0.056***	−0.034**	−0.102***	0.039***	−0.542***	1			
LnAge	−0.027	−0.021	0.049***	−0.047***	0.096***	−0.104***	1		
LnNstaff	0.111***	0.074***	0.319***	−0.222***	0.259***	−0.291***	−0.069***	1	
Soe	0.038**	0.036***	0.092***	−0.211***	0.268***	−0.259***	0.093***	0.257***	1
A_Slack	−0.036*	−0.021	−0.078***	−0.291***	−0.562***	0.390***	−0.108***	−0.251***	−0.182***
U_Slack	−0.056***	−0.044***	−0.077***	−0.252***	−0.663***	0.406***	−0.085***	−0.201***	−0.175***

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.

refer to Herold et al. (2006) and Peng et al. (2010) and measure A_Slack by dividing current assets by current liabilities and measure U_Slack by dividing owners' equity by total liabilities. In addition, in order to avoid the multicollinearity problem caused by multiplying mediating variables and independent variables, we centralize these variables according to the suggestion of Toothaker (1994).

Drawing on existing studies (Qi et al., 2018), we control for several variables. Frist, R&D investment represents the importance firms attach to innovation activities (Li and Liu, 2021). Next, debt ratio (Debts) is to control for the corporate debt ratio, which is related to innovation investment. Additionally, firm scale (*LnNstaff*) is to control for innovation strategy differences between larger and smaller companies (Wu et al., 2018). Tobin's Q ratio (*Tonbinq*) is in the regression in order to capture the investment opportunity differences across firms (Eger and Mahlich, 2014). Firm ownership (*Soe*) is a dummy for state-owned firms (SOE), and Firm age (*LnAge*) is to control for the fact that older firms may generally have more experience and problem-solving skills than younger ones (Wu and Qu, 2021). The definitions of the variables are summarized in Table 1.

3.2.2 Descriptive statistics and analysis

Table 2 reports the descriptive statistics each of the variables. The minimum value of green patents authorized is 0, and the maximum is 442, with a standard deviation of 22.78, indicating large variation in the number of green patents authorized among all firms. The CSR ratings have a minimum of 11.85 and a maximum of 87.95, with a standard deviation of 14.15, again pointing to a large difference in CSR performance among the firms. The average score of CSR was 38.10 points, indicating that China's CSR is still in its infancy.

Table 3 shows the correlation coefficient matrix of the variables. The results indicate that: 1) the correlation

TABLE 4 CSR performance and green innovation output.

Variables	Green patents authorized	Green invention patents authorized
	GIt+1 (1)	GIIt+1 (2)
CSR	0.732***	0.780***
	(4.96)	(4.49)
LnNstaff	0.426	0.573
	(0.42)	(0.61)
LnAge	−4.729	1.477
	(−1.18)	(0.41)
Debts	−14.971	−0.192
	(−1.55)	(−0.02)
Tonbinq	−0.647	0.264
	(−0.55)	(0.21)
Rd	−0.140	0.019
	(−0.37)	(0.05)
Soe	5.667	7.105*
	(1.56)	(1.91)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Constant	−49.529**	−77.725***
	(−2.15)	(−3.16)
N	1419	1419
r2_p	0.0601	0.0714

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Robust t-statistics in parentheses.

coefficient of CSR and total green patents authorized is statistically positive at the 1% significance level, suggesting a positive correlation between CSR performance and green technological innovation; and 2) the correlation coefficients between most control variables are less than 0.5, indicating that the problem of multicollinearity is not serious in our model.

4 Empirical results and analysis

4.1 Corporate social responsibility and green technology innovation

Table 4 displays the empirical results of CSR performance and green technology innovation estimations with fixed-effect panel data method. Column (1) includes the regression results of CSR performance, firm scale, firm age, debt ratio, Tobin's Q ratio, R&D investment, firm ownership the industry effect, and the year effect. The coefficient of CSR is statistically positive (0.732***) at the 1% significance level, indicating that firms with better CSR performance had a higher number of green patents.

Among invention patents, utility model patents, and design patents, invention patents can better reflect innovation at advanced technological levels. With other conditions unchanged, the higher the number of green invention patents authorized, the greater the quantity of a firm's green innovation. Further, we also examined the impact of CSR on the number of green invention patents authorized. Column (2) of Table 4 presents the results using green invention patents authorized as the indicator for green technology innovation, which show that the estimation coefficient on CSR is statistically significantly positive (0.780***) at the 1% significance level. This result suggests that CSR is positively related to quantitative measures of green technology innovation.

4.2 The moderating effects of both types of slack resources

In Table 5, we present the moderating effect of slack resources on the relationship between CSR performance and green technology innovation. Column (1) shows that the coefficient of the interaction term of *CSR* and firm *A_Slack* is 0.043 (statistically insignificant), so we cannot

TABLE 5 The moderating effects of different types of slack resources.

Variables	Green patents authorized GIt+1		Green invention patents authorized GIIt+1	
	(1)	(2)	(3)	(4)
CSR	0.765***	0.783***	0.782***	0.799***
	(4.96)	(4.49)	(4.69)	(4.84)
A_Slack	−0.121		−0.129	
	(−0.19)		(−0.18)	
U_slack		0.335		0.346
		(0.36)		(0.37)
ASla*csr	0.082		0.086	
	(1.30)		(1.31)	
USla*csr		0.089*		0.105*
		(1.67)		(1.66)
LnNstaff	0.413	0.361	0.475	0.547
	(0.42)	(0.61)	(0.48)	(0.55)
LnAge	−4.714	−4.375	−5.172	−5.262
	(−1.18)	(0.41)	(−1.26)	(−1.28)
Debts	−14.962	−12.954	−14.640	−11.809
	(−1.55)	(−0.02)	(−1.49)	(−1.09)
Tonbinq	−0.644	−0.554	−0.792	−0.781
	(−0.55)	(0.21)	(−0.67)	(−0.66)
Rd	−0.35	−0.346	−0.367	−0.489
	(−0.37)	(0.05)	(−0.82)	(−1.13)
Soe	5.667	5.585	5.466	5.185
	(1.56)	(1.91)	(1.53)	(1.45)
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Constant	−49.529**	−48.831***	−51.041**	−53.892**
	(−2.15)	(−3.16)	(−2.21)	(−2.32)
N	1419	1419	1419	1419
r2_p	0.0601	0.0714	0.0604	0.0606

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Robust t-statistics in parentheses.

conclude that *A_Slack* plays a role in moderating the relationship between CSR and green technology. From a practical point of view, we may explain this by supposing that as firms pursue profit maximization in the short term, they might not consider inputting *A_Slack* into green innovation in their short-term decisions. Columns (2) and (4) show that the coefficient of the interaction term of *CSR* and *U_Slack* is 0.089 and 0.105 (10% significance), implying that *U_Slack* positively moderates the positive correlation between CSR performance and green technology innovation output.

4.3 Robustness test

4.3.1 Two-stage Tobit IV regression

Due to the complexity of firm green technology innovation, it is difficult to encompass all influencing factors in a single model, and the omission of important variables is therefore a common source of endogeneity in related studies. Following Chen et al., 2017, we adopt a two-stage Tobit instrumental variable (IV) method to carry out regressions by adding CSR lagged by one period (L.CSR) and two periods (L2.CSR) as IVs to avoid endogeneity problems to some extent. Here, the control

TABLE 6 Two=Stage tobit IV results.

Variables	Green invention patents authorized	Corporate social responsibility	Green invention patents authorized
	First-stage regression	Second-stage regression	
	IV1	IV2	IV2
LnNstaff	0.014	0.368***	0.013
	(0.01)	(2.74)	(0.01)
LnAge	−15.545***	0.256	−15.498***
	(−3.01)	(0.43)	(−3.02)
Debts	−31.370**	−2.546*	−31.348**
	(−2.33)	(−1.69)	(−2.34)
Tonbinq	−4.057**	−0.124	−4.042**
	(−2.48)	(−0.73)	(−2.48)
Rd	−0.567	−0.042	−0.569
	(−1.12)	(−0.66)	(−1.13)
Soe	3.273	−0.114	3.268
	(1.00)	(−0.30)	(1.00)
U_Slack	−0.092	−0.042	−0.096
	(−0.07)	(−0.32)	(−0.08)
L.CSR		0.827***	
		(29.12)	
L2.CSR		0.105***	
		(3.58)	
CSR	0.733***		0.732***
	(5.15)		(5.16)
Industry FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Constant	21.150	0.359	21.206
	(0.78)	(0.13)	(0.78)
Observations	904	904	904
N	904	904	904

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Z-statistics in parentheses.

variables are the same as before. The first-stage results in Table 6 show that CSR's mean values across both industries and regions are statistically positively correlated with green patents authorized (1% level). Additionally, the F-statistic of the weak instrument test is 115.50, which is far higher than 10, indicating that the IV is valid. The second-stage regression results show that after controlling for the action channel of endogenous problems that may be caused by omitted variables, the previous regression conclusions from Sections 4.1, 4.2 remain valid.

4.3.2 Changing the measurement of the independent variables

Measurement bias of the key independent variable CSR can lead to biased coefficient estimation or inconsistency in the model. For this reason, drawing on Zhang et al. (2019), we now use the CSR ratings published by hexun.com as a proxy variable of CSR and conduct our regressions again. Control variables remain unchanged, and the results are shown in Table 7. Columns (1) and (2) show that the signs and significance of the effects of CSR represented by proxy variables are consistent with the previous results, indicating the robustness of our conclusions in this respect.

4.3.3 Changing the measurement of the dependent variables

Measurement bias of green technology innovation can lead to endogeneity problems. Based on Qi et al. (2018) and Akcigit et al. (2016), we thus carry out regressions adopting the proportion of green patents authorized and the quality of green patents authorized as the proxies of green technology

TABLE 7 Changing the measurement of the independent variables.

Variables	Number of green patents authorized	Number of green invention patents authorized
	(1)	(2)
CSR	0.165***	0.150***
	(2.94)	(2.74)
U_slack	0.317	0.334
	(0.35)	(0.37)
USla*csr	0.069*	0.086*
	(1.68)	(1.67)
Control variables	Yes	Yes
Industry FE	Yes	Yes
Year FE	Yes	Yes
Constant	−22.297	−46.127**
	(−1.10)	(−2.28)
N	1546	1546
r2_p	0.0563	0.0644

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Robust t-statistics in parentheses.

TABLE 8 Changing the measurement of the dependent variables.

Variables	Share of green patents authorized	Quality of green patents authorized
	(1)	(2)
CSR	0.003***	0.003***
	(3.67)	(3.05)
U_slack	0.232	0.275
	(0.29)	(0.27)
USla*csr	0.059*	0.028*
	(1.68)	(1.67)
Control variables	Yes	Yes
Industry FE	Yes	Yes
Year FE	Yes	Yes
Constant	−0.371	0.492***
	(−1.22)	(3.11)
N	1419	672
r2_p	0.248	0.600

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Robust t-statistics in parentheses.

innovation and use the patent knowledge width method according to the previous research of Aghion et al. (2015) and Akcigit et al. (2016). Corporate patent knowledge width refers to the level of complexity of the knowledge contained within a certain patent and reflects patent quality in terms of the complexity and extensiveness of the knowledge contained by patents. This metric is beneficial for overcoming the inadequacy of using only the quantitative dimension of patents to measure firm innovation activities. Since patents serve as important carriers of innovative knowledge oftentimes with significant economic value, the level of complexity of the knowledge contained in patents necessarily affects the quality of patents. The more complex the knowledge contained within a patent, the more difficult it is to mimic and improve on that patent. Furthermore, patents protected by the State Intellectual Property Office, get monopoly rights to their patents. This can profoundly affect corporate performance. The results of our regressions using this measure of green patent quality are presented in Columns (1) and (2) of Table 8. The signs of the coefficients are consistent with the previous results and are all statistically significant at the 1% level, indicating the robustness of the above conclusions in this respect.

4.3.4 Additionally lagged green technology innovation

Considering the uncertainties and extended processes from R&D to patent authorization of green technology innovation in the case of China, we now lag the output of green technology innovation by *t*+2 and *t*+3 periods referring to Fang et al. (2014). The regression results are presented in Columns (1) and (3) of Table 8. Column (1) shows that the estimated coefficients of the effects of lagged green technology innovation output are statistically positive (1% level). Column (2) shows that the estimated coefficients of the moderating effect of *U_Slack* on lagged green technological output are statistically significant at the 10% level. Column (3) shows that the estimated coefficients of

TABLE 9 Additionally lagged green patents authorized.

Variables	Number of green patents authorized in t + 2 periods	Number of green patents authorized in t + 2 periods	Number of green patents authorized in t + 3 periods
	(1)	(2)	(3)
CSR	0.707***	0.697***	0.624***
	(4.67)	(4.55)	(4.03)
U_slack		0.168	0.124
		(0.17)	(0.17)
USla*csr		0.044*	0.017
		(1.67)	(0.67)
Control variables	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Constant	−38.161*	−31.660	−23.766
	(−1.69)	(−1.37)	(−1.07)
N	1177	954	743
r2_p	0.0596	0.0637	0.0722

***, **, and * represent $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.
Robust t-statistics in parentheses.

the moderating effect of *U_Slack* on lagged green technological output are not statistically different from 0. These results indicate that the conclusions of this study have no serious lagged correlation and that the above conclusions are robust in this respect (Table 9).

5 Conclusion

This study explored the relationship between CSR performance and firm green technology innovation with firm slack resources as mediating variables. We find that different slack resource types have different influences on the relationship between CSR performance and green technology innovation. Our regression results show that good CSR performance relates positively to green technology innovation and that firm slack resources play a partial mediating role. A larger amount of unabsorbed slack resources strengthens the positive relationship of CSR performance on green technology innovation (Aghion et al., 2005; Surroca et al., 2010; Schiederig et al., 2012; Kawai et al., 2018; Zhang et al., 2022b; Peng et al., 2014; Shen et al., 2020).

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: www.csmar.com and cpquery.cnipa.gov.cn.

Author contributions

YX completed this thesis independently.

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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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Determinants of villagers' satisfaction with post-disaster reconstruction: Evidence from surveys ten years after the Wenchuan earthquake

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Residents' satisfaction with post-disaster reconstruction in earthquake-stricken areas directly affects their quality of life, which cannot be ignored in post-disaster reconstruction. More than 10 years after the Wenchuan earthquake, we took ten randomly selected villages in the five areas hardest-hit by the Wenchuan earthquake as research objects and obtained 483 valid completed questionnaires. The villagers were randomly sampled and descriptive statistical analysis, factor analysis, and ordered logistic regression were used to explore the factors and relationships influencing villagers' satisfaction with post-disaster reconstruction in Wenchuan earthquake-stricken areas. The results show that: 1) the more rural residents know about the post-disaster reconstruction, the greater their level of satisfaction; 2) the more the annual income of families increases after resettlement, the greater the satisfaction of rural residents with the post-disaster reconstruction; 3) six public factors, namely the village committee acts as, housing construction quality, public service, policy of benefiting farmers, cultural environment, and hardware environment, all significantly positively affect residents' overall satisfaction with post-earthquake reconstruction. This study thus enriches the theory of residents' satisfaction studies and the practice of post-earthquake reconstruction.

KEYWORDS

earthquake-stricken area, post-disaster reconstruction, satisfaction analysis, factorial analysis, ordered logistic regression

1 Introduction

Since the 20th century, there have been nearly a thousand earthquakes of magnitude 6 or above in China, and their seismic activities have been characterized by high frequency, high intensity, and wide distribution (Xie and Zhang, 2005; Ao et al., 2021). Among them, the Wenchuan earthquake occurred in the Longmenshan seismic belt, and was in the northeast–southwest direction, and there were six earthquakes of magnitude six or above, and the largest earthquake was the Wenchuan earthquake of magnitude 8.0 in 2008 (Jiang, 2009). According to statistics, the Wenchuan earthquake was an unprecedented disaster, with the hardest-hit area exceeding 100,000 square kilometers, involving 6 cities and counties, 88 counties and cities, 1,204 towns and villages, and 27.92 million people. In Sichuan Province alone, more than four million houses collapsed or were damaged, and the infrastructure for water, electricity, and transportation suffered serious damage (China Government Affairs Monitoring Center, 2008).

Research into the damage caused by earthquakes to human production and life and the associated coping strategies has been a focus of scholars all over the world (Bryant, 1991). High-intensity earthquakes can destroy urban and rural construction in disaster-hit areas to varying degrees. To restore order to life in disaster areas as soon as possible and explore scientific and efficient modes of reconstruction, post-disaster reconstruction has become an important concern of experts around the world (Shi, et al., 2021). At the same time, there is also the issue of people's livelihoods that needs special attention in the post-disaster reconstruction of residential areas and when striving to improve rural residents' life satisfaction. To date, research into the post-disaster reconstruction of settlements has mostly focused on large cities, with less attention paid to people's satisfaction with the post-disaster reconstruction of settlements in rural areas (Li and Tian, 2015; Yang, 2017).

Satisfaction is an individual's subjective experience of his or her own quality of life, an individual's comprehensive cognitive judgment of life, which reflects an individual's general evaluation of their overall life and is influenced both by their own factors and environmental factors (Song et al., 2019). Individual differences among rural residents will lead to differences in their perceptions of a centralized living style in post-disaster reconstruction settlements, resulting in different degrees of acceptance and satisfaction with post-disaster reconstruction settlements (Peng et al., 2018a). Blakely pointed out that the post-disaster reconstruction of residential areas not only involves disaster prevention and emergency rescue considerations but also the re-planning and reconstruction of a region. The first priority is definitely the emergency planning when a disaster occurs, but more important is the functional allocation of the region, such as infrastructure, environmental planning, economic development planning, new residence resettlement, and so on (Hu, 2008). These living environment factors will affect rural residents' satisfaction with the post-disaster reconstruction of residential areas.

Most of the previous analyses conducted were from the perspective of the government. This study, on the other hand, analyzes post-disaster reconstruction settlements from the perspective of individual villagers and tries to understand rural residents' satisfaction with post-disaster reconstruction settlements in Sichuan Province. We established a system of the factors influencing rural residents' satisfaction with post-earthquake reconstruction of residential settlements, based on existing research, and explored rural residents' overall satisfaction with post-disaster reconstruction settlements and the corresponding influencing factors and their relationships. The significant influencing factors were determined based on empirical studies, providing theoretical and practical support for post-disaster reconstruction practice.

The structure of this paper is shown in Figure 1: Section 2 reviews the literature, Section 3 describes the research methods and data sources, Section 4 presents the empirical results and discusses the results, Section 5 summarizes the full text and proposes prospects for future research, and the final section presents the limitations of this study.

2 Literature review

China has adopted a variety of reconstruction policies for post-earthquake reconstruction in rural areas, including three main ways of overall construction, overall self-construction, and self-construction and maintenance (Peng, et al., 2013). Under the joint action of the family characteristics and production and management goals of rural residents, different types of farmers will be formed, and different types of farmers will have different positioning of maximizing the comprehensive benefits of the family, which will directly affect the decision-making behavior and mode selection of rural settlements post-disaster reconstruction (Steinberg, 2007).

Previous research into post-earthquake reconstruction has emphasized keeping pace with the times and combining corresponding development policies for reconstruction areas. For urban post-disaster reconstruction, Zhou and Xia (2008) suggested that post-earthquake reconstruction planning should follow the development strategy of "shaping an international tourist city", relocating urban functional departments and residents from severely damaged old cities to new areas, and relocating old urban areas to new areas, which should be transformed into economic development functional areas with cross-services of multiple industries. Yu et al. (2021) proposed that as rural social relations are complex, it is necessary to pay more attention to social connection and regional capacity building when planning post-earthquake reconstruction in rural areas and to maximize the flexibility of reconstruction strategies to form an adaptive mechanism for post-disaster recovery. When verifying the role and impact of participation in post-earthquake reconstruction, Wang (2018) believed that participatory post-disaster rural reconstruction could provide a basis for targeted poverty alleviation, rural revitalization, and urban and rural development.

Post-disaster reconstruction is a common behavior of social norms and government intervention. Guo and Fang (2019)

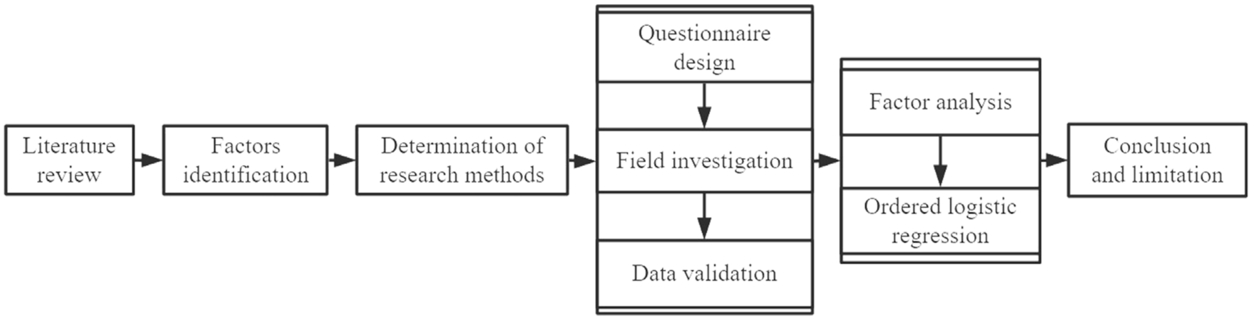

FIGURE 1
Technology roadmap.

investigated rural residents' satisfaction with basic public services in rural areas. Their results showed that rural residents' satisfaction is influenced by gender, age, culture, income level, farmers' participation, and understanding of basic public services. Different individual and family characteristics of rural residents for post-disaster reconstruction residential satisfaction exist. Satisfaction with post-disaster reconstruction and resettlement shows a decreasing trend with increasing age. The higher the education level of rural residents, the greater their satisfaction with post-disaster reconstruction settlements (Yang, 2014). In addition, differences in income sources will have an impact on villagers' satisfaction. Sun and Chen (2016) investigated the factors influencing rural residents' satisfaction with resettlement in M Town, Jiangsu Province, and found that farmers with a larger proportion of non-agricultural income after resettlement in this area were less satisfied with this resettlement. The reason may be that for these farmers, the compensation of this resettlement is less attractive to them and their overall satisfaction is not high. Peng et al. (2018b) point out that the earthquakes cause serious damage to cultivated land, land consolidation and reclamation directly affected farmers' economic income, and the process of rebuilding residential areas was an important opportunity to improve economic development. The diversification of rural residents' incomes should be increased to make farmers' income no longer unitary.

In addition to the above-mentioned personal factors, satisfaction with the post-disaster reconstruction of residential areas is also affected by living environment factors (Song et al., 2019; Yang, et al., 2021). Jansen (2014) suggested that living satisfaction depends on personal expectations and that when housing does not meet the needs of residents, it will directly reduce their living satisfaction. Cao (2016) analyzed satisfaction with the living environment, with categories including housing orientation, supporting facilities, housing quality, and neighborhood relationships. Aulia and Ismail, 2013 further categorized the external influencing factors into the natural environment, equipment conditions, property services, and traffic conditions, to analyze the factors influencing living satisfaction.

The actions of village committees or communities will have an impact on villagers' satisfaction with reconstruction. In a study of new rural construction, Hu (2016) put forward the notion that the working ability of grassroots village committee cadres and rural residents' awareness of rural construction policies will affect rural residents' satisfaction with village-level democratic system construction and cultural construction. In the process of resettlement housing allocation, Xiao et al. (2014) evaluated satisfaction with the residential areas rebuilt after an earthquake from the perspective of the affected residents and found that the disclosure of the information channel of the housing redistribution system in the rebuilt residential areas had a major influence on the resettled residents' satisfaction. Hu conducted a comparative study of the reconstruction of New Orleans in the United States and the reconstruction after the Wenchuan earthquake in China. He found that communication with local residents should be emphasized at the beginning of the reconstruction policy formulation process, and they should be invited to participate in the reconstruction process and have their opinions listened to, which is not only conducive to the application of the reconstruction policy but also helps to rebuild the confidence of local people (Hu, 2008). Paying attention to rural housing reconstruction for farmers is key to realizing sustainable recovery. The reconstruction policy has different decisions on the reconstruction of village houses damaged to varying degrees, while publicity about the reconstruction policy can clarify affected people's perceptions of post-disaster reconstruction (Peng et al., 2018b). Wang et al. (2012) pointed out that the dissemination of knowledge about earthquake disaster prevention is an important factor affecting residents' life satisfaction.

Housing construction is the top priority of post-earthquake reconstruction. According to the disaster reduction plan and regulations of the China Earthquake Administration (CEA) from 2007 to 2019, local rural housing construction planning should be supervised in terms of site selection, avoidance of earthquake prone areas, and construction quality to ensure housing safety, and skilled technicians should be trained to master earthquake knowledge (Wu and Wu, 2020). Cassidy (2007) proposed that when a disaster occurs, the maximum duration of temporary shelter provided by the government should be 5 years, so that the construction period of post-earthquake reconstruction settlements should not exceed the maximum duration that victims can bear. At the same time, post-disaster reconstruction projects should have clear start and completion dates (Davidson et al., 2007).

Steinberg (2007) summarized the experience of post-disaster reconstruction in Aceh and Nias in Indonesia and pointed out that the construction of residential buildings as part of post-disaster reconstruction was only the first step of reconstruction; the construction of the surrounding environment and public facilities should also be a focus of post-disaster reconstruction. Transportation is very important in post-disaster reconstruction. If roads are blocked, much of the transport of reconstruction materials will be affected. Therefore, post-disaster reconstruction of traffic systems should be a basic and pilot project (Kun, 2013). At the same time, public facilities, such as water, electricity, and communication, should also be a focus of the reconstruction of post-disaster settlements, and factors such as whether the quality of drinking water, the convenience of water use, and power supply and communication meet the needs of residents can also affect their satisfaction with post-disaster reconstruction settlements (Curti et al., 2008).

The existing research shows that relevant policies that benefit farmers will also have an impact on villagers' satisfaction with reconstruction. Developing characteristic agriculture to diversify agriculture, developing agricultural training, and introducing non-agricultural industries will enable young laborers to engage in non-agricultural work, which will increase farmers' income. This will help to make up for the increased cost of living after the disaster, which will improve rural residents' satisfaction with the reconstruction of settlements following a disaster. In addition, as the land belongs to rural collectives, after many rounds of discussion by the village committee, even the land adjustment should not encounter any difficulties, which will help to reassure residents that problems of land reclamation or cultivated land demand can be solved following a disaster (Peng et al., 2013). At the same time, the human environment is also a key point that cannot be ignored. Earthquake disasters in Sichuan Province mostly occur in areas with superior natural conditions and profound cultural heritage. Post-earthquake reconstruction should pay attention not only to the protection of the natural environment but also to the reconstruction of national cultural traditions (Li and Shi, 2008).

Therefore, it is of great theoretical and practical significance to systematically explore residents' degree of satisfaction with post-disaster reconstruction to further improve residents' quality of life and enhance public participation in post-disaster reconstruction.

3 Methodology

3.1 Questionnaire design

For this study a questionnaire was designed according to the existing related research and the current situation of post-earthquake reconstruction of residential areas. The questionnaire comprised two parts: social-demographic information and a post-disaster reconstruction satisfaction survey scale.

Basic personal information of respondents (shown in Table 1) and family information was collected (shown in Table 2).

The satisfaction scale measured respondents' satisfaction with 28 elements of post-disaster reconstruction and was coded with a five-point Likert scale, with the lowest level of satisfaction being 1 and the highest level of satisfaction being 5 (Yang et al., 2020c). Details of the post-disaster reconstruction satisfaction scale and its measurement instructions are shown in Table 3.

3.2 Model specification

Several types of models have been used to study people's satisfaction with the built environment, including multiple regression models (Yang et al., 2022; Xu, 2020), structural equation models (Song et al., 2019; Kostas, 2020; Wang et al., 2020; Seongyeon and Christine, 2009; Chen et al., 2014; Margareta et al., 2018), a CCSI model (Zhou and Wang, 2022), ordered logistic regression analysis (Mao, 2022; Junghwa et al., 2020), and a Bayesian multilevel ordinal response model (Zhai et al., 2021). However, there has been limited research into the factors influencing residents' satisfaction and their relationships in post-disaster reconstruction, which restricts the rationality of the formulation of post-disaster reconstruction policies. The dependent variable used in the present study was satisfaction, a categorical variable with differences in degrees. Therefore, factor analysis was mainly used to reduce the dimension of influencing factors (Ao, et al., 2020), and an ordered logistic regression model was used to analyze the relationship between influencing factors and the satisfaction with post-earthquake reconstruction. In logistic regression analysis, when the variable level is greater than two and it is an ordered variable, ordered logistic regression analysis can be used. As the dependent variable in this study was satisfaction, the options were completely dissatisfied, not very satisfied, generally satisfied, comparatively satisfied, and very satisfied, which were suitable

TABLE 1 Description of basic personal information of respondents.

Variable	Variable declaration	Variable type
Gender	1 = Male; 2 = Female	Categorical variable
Age	The corresponding numerical value is the corresponding age For example: 25 = 25 years old	Continuous variable
Education level	1 = Uneducated; 2 = Primary School; 3 = Junior High School; 4 = Senior High School; 5 = University or above	Categorical variable
Is the current place of residence the birthplace?	Yes = 1,No = 0	Binary variable
Participate in the reconstruction decision-making process?	Yes = 1, No = 0	Binary variable
Have you received education on disaster prevention and mitigation?	Yes = 1, No = 0	Binary variable
Have you experienced secondary disasters after the earthquake?	Yes = 1, No = 0	Binary variable
Understanding of post-disaster reconstruction management regulations	Very little understanding = 1, A little understanding = 2, General understanding = 3, Better understanding = 4, Very understanding = 5	Sequence variable
Understanding of seismic fortification level of buildings	Very little understanding = 1, A little understanding = 2, General understanding = 3, Better understanding = 4, Very understanding = 5	Sequence variable
Understanding of post-disaster reconstruction methods	Very little understanding = 1, A little understanding = 2, General understanding = 3, Better understanding = 4, Very understanding = 5	Sequence variable

TABLE 2 Description of respondents' family information.

Variable	Variable declaration	Variable type
Number of residential floors	1 = 1, 2 = 2, 3–6 = 3, Layer 7 and above = 4	Sequence variable
Was the rebuilt house completed on time?	Yes = 1, No = 0	Binary variable
Post-earthquake reconstruction	Overall construction = 1, overall self-construction = 0	Binary variable
Annual household income after earthquake	Ten thousand yuan	Continuous variable
Stability of main household income after resettlement	Unstable = 1, stable = 0	Binary variable
Changes of annual household income after resettlement	Significant increase = 1, some increase = 2, no change = 3, some decrease = 4, significant decrease = 5	Sequence variable
Main income sources of families before the earthquake	Farming/fruit and vegetable planting, poultry/aquaculture, farmhouse tourism, land circulation, working outside, and others	Categorical variable
Main source of family income after earthquake resettlement	Farming/fruit and vegetable planting, poultry/aquaculture, farmhouse tourism, land circulation, working outside, and others	Categorical variable

for ordered logistic regression analysis. The logistic regression model used in this study is expressed as follows:

$$Ln\left[\frac{p(y\le j)}{1-p(y\le j)}\right]=\alpha_j+\sum_{i=1}^{n}\beta_i x_i \tag{1}$$

where j = 1, 2, 3, 4, and 5, representing the five levels of satisfaction; y is residents' satisfaction with reconstruction; x_i is the explanatory variable and control variable that affects farmers' life satisfaction; α_j is the intercept parameter; and β_j is the regression coefficient, which indicates the direction and degree of influence of explanatory variables on the explained variables.

3.3 Sample selection and data collection

According to the degree of the Wenchuan earthquake disaster, the population, economy, industry, and employment status, combined with the vigilance of rural residents and the degree of cooperation reflected, this study randomly selected

TABLE 3 Post-disaster reconstruction satisfaction survey scale variables.

Variable		References	Satisfaction		Variable type
			Minimum	Minimum	
F1	Subsidy guarantee	Alparslan et al. (2008)[4] Morimoto (2012)	1	5	Sequence variable
F2	Information channel	Xiao et al. (2014) Ye et al. (2017)	1	5	Sequence variable
F3	Education and publicity of disaster prevention and mitigation	Wang et al. (2012) Zhou and Liao (2015) Li and Shi. (2008)	1	5	Sequence variable
F4	Reconstruction policy propaganda	Peng et al. (2018b) Qu et al. (2012) Li and Shi. (2008)	1	5	Sequence variable
F5	Reconstruction decision-making participation	Li and Shi (2008) Zhou and Liao (2015) Wang (2018)	1	5	Sequence variable
F6	Type of layout of apartment	Cinicioglu et al. (2007) Feyza et al. (2007)	1	5	Sequence variable
F7	House safety	Ergonul (2005); Wu and Wu (2020)	1	5	Sequence variable
F8	Quality of building materials	Ergonul (2005); Wu and Wu (2020) Cinicioglu et al. (2007)	1	5	Sequence variable
F9	Technology of constructors	Ergonul (2005); Cinicioglu et al. (2007); Wu and Wu (2020)	1	5	Sequence variable
F10	Reconstruction duration	Ergonul (2005); Davidson et al. (2007)	1	5	Sequence variable
F11	Drinking water quality	Curti et al. (2008)	1	5	Sequence variable
F12	Water convenience	Curti et al. (2008)	1	5	Sequence variable
F13	Power supply demand	Curti et al. (2008)	1	5	Sequence variable
F14	Communication requirements	Curti et al. (2008)	1	5	Sequence variable
F15	Planting space around housing	Li and Shi (2008)	1	5	Sequence variable
F16	Cultivated land distance	Li and Shi (2008)	1	5	Sequence variable
F17	Land reclamation	Ansal et al. (2009); Peng et al. (2013) Mahdi and AsgharAlesheikh (2011)	1	5	Sequence variable
F18	Agricultural training	Ansal et al. (2009); Peng et al. (2013) Mahdi and AsgharAlesheikh (2011)	1	5	Sequence variable
F19	Agricultural diversification	Ansal et al. (2009); Peng et al. (2013) Mahdi and AsgharAlesheikh (2011)	1	5	Sequence variable
F20	Non-agricultural industry introduction	Ansal et al. (2009); Peng et al. (2013) Mahdi and AsgharAlesheikh (2011)	1	5	Sequence variable
F21	Talent education	Speare (1974)	1	5	Sequence variable
F22	Policies and systems	Li and Shi (2008)	1	5	Sequence variable
F23	Cultural tradition	Speare (1974); Li and Shi (2008)	1	5	Sequence variable

(Continued on following page)

TABLE 3 (*Continued*) Post-disaster reconstruction satisfaction survey scale variables.

Variable		References	Satisfaction		Variable type
			Minimum	Minimum	
F24	Earthquake shelter	#FF0000 Wen (2001)	1	5	Sequence variable
F25	Road planning	Kun (2013) (Zhou et al., 2019)	1	5	Sequence variable
F26	Road quality	Steinberg (2007); Kun (2013)	1	5	Sequence variable
F27	Sanitary environment/village appearance	Inneke et al. (2013) MacAskill and Guthrie (2015)	1		Sequence variable
F28	Natural environment	Curti et al. (2008); Li and Shi (2008)	1	5	Sequence variable

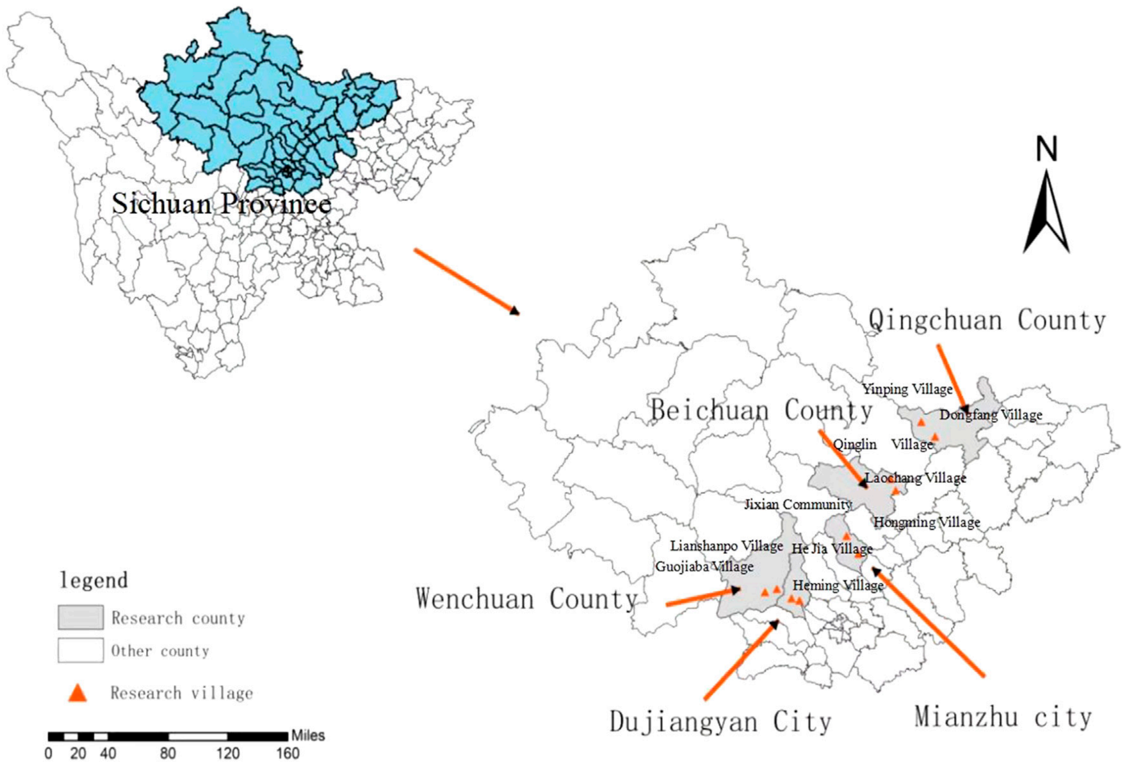

FIGURE 2
The location of the sample villages.

10 sample villages in the 5 hardest-hit areas in Sichuan Province, with the geographical location of each village shown in Figure 2.

The field investigation part of this study was conducted from January 1 to January 5, 2019. The research team was divided into five groups, each of which was responsible for data collection in two sample villages. The research team entered the village and randomly selected residents of the village to complete the questionnaire survey. If a resident did not accept the invitation to take part in the survey, the researchers randomly selected the next household. In this study, 516 face-to-face questionnaires were completed, of which 33 questionnaires with missing information or internal inconsistencies were

TABLE 4 Sample villages and the numbers of questionnaires collected.

Investigation site		Degree of disaster	Reconstruction of settlement pattern	Number of questionnaires
Deyang city	Jixian Community, Hanwang Town, Mianzhu City	Severe disaster	Centralized residence	50
	Hongming Village, xinan town, Mianzhu City	Severe disaster	Decentralized residence	49
Dujiangyan city	Heming Village, LiujieTown	Severe disaster	Centralized residence	48
	He Jia Village, Anlong Town	Severe disaster	Decentralized residence	47
Guangyuan city	Dongfang Village, Qingxi Town, Qingchuan County	Severe disaster	Centralized residence	52
	Yinping Village, Qingxi Town, Qingchuan County	Severe disaster	Centralized residence	45
Aba Autonomous Prefecture	Guojiaba Village, Shuimo Town, Wenchuan County	Severe disaster	Centralized residence	49
	Lianshanpo Village, Shuimo Town, Wenchuan County	Severe disaster	Decentralized residence	42
Mianyang city	Laochang Village, Chenjiaba Town, Beichuan Qiang Autonomous County	Severe disaster	Centralized residence	51
	Qinglin Village, Chenjiaba Town, Beichuan Qiang Autonomous County	Severe disaster	Centralized residence	50

TABLE 5 Basic statistical information about respondents.

Variable	Variable declaration	Percentage (%)	Number of samples	Variable	Variable declaration	Percentage (%)	Number of samples
Gender	Male	45.25	219	Level of education	Without education	14.49	70
	Female	54.75	264		Primary school	30.85	149
Age	15–30 years old	16.56	80		Junior school	30.85	149
	30–45 years old	21.33	103		Technical secondary school	4.97	24
	45–60 years old	35.20	170		Senior high school	10.14	49
	60–75 years old	22.57	109		Junior college	5.59	27
	More than 75 years old	4.34	21		University or above	3.11	15
Number of residential floors	1	36.44	176	Sources of family income before the earthquake	Farming/fruit and vegetable growing	30.23	147
	2	48.45	234		Poultry/aquaculture	13.04	63
	3–6	14.70	71		Farmhouse tourism	3.52	17
	7 or more	0.41	2		Land circulation	1.24	6
Annual household income after earthquake	<10,000	22.57	109		Working outside	36.65	177
	10,000–50,000	62.32	301		Other	15.32	73
	50,000–100,000	12.84	62	Sources of household income after the earthquake	Farming/fruit and vegetable growing	15.32	74
	>100,000	2.27	11		Poultry/aquaculture	3.73	18
Changes in annual household income after resettlement	Some increase	54.24	262		Farmhouse tourism	3.73	18
	No change	34.37	166		Land circulation	3.52	17
	Some decrease	9.32	45		Working outside	50.31	243
	Significant decrease	2.07	10		Other	23.39	113

excluded. In total, 483 valid questionnaires were included. Table 4 shows the sample villages and the number of questionnaires collected from each, while Table 5 presents the basic statistical information about the respondents. The changes in the main sources of household income before and after the earthquake are shown in Figure 3.

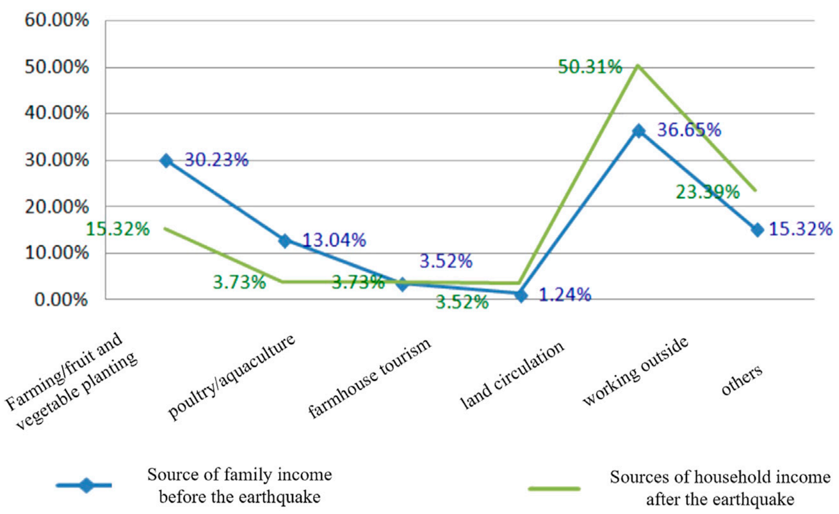

FIGURE 3
Major sources of income for households before and after the earthquake.

4 Results and discussion

4.1 Exploratory factor analysis

In this study, SPSS software version 23.0 was used to conduct exploratory factor analysis (EFA) of 28 variables relating to post-disaster reconstruction satisfaction, to determine the influence of each factor on the overall satisfaction with post-disaster reconstruction. To test the applicability of the factor analysis, we used the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test to explore the applicability of factor analysis of the 28 satisfaction measurement variables. The test results showed that the KMO value was 0.882 and the p-value was 0.000. Thus, the results showed that there was a high correlation among the 28 satisfaction measurement variables, which indicated that these data were suitable for the EFA method. The factor analysis results of the 28 satisfaction indexes are shown in Table 6 Variables with a factor load of less than 0.4 were considered to be nonsignificant variables, so F15 was deleted (indicated by "–" in the Table). EFA finally determined six common factors.

4.2 Multiple collinearity analysis

The multiple collinearity problem may lead to a low level of significance of various spatial variables. Therefore, it is necessary to investigate the multiple collinearity of these independent variables (Ding, et al., 2017; Yang, et al., 2020a; Yang et al., 2020b; Zhao, et al., 2020; Yang, et al., 2022). To test multiple collinearity, we mainly used the variance inflation factor (VIF). With a higher VIF value, a specific explanatory variable is more likely to be expressed by the linear function model of other explanatory variables, and there may be multiple collinearity problems in the model. The maximum VIF value of the explanatory variable in this study was 2.094, which showed that there was no multiple collinearity problem. The results of multivariate multiple collinearity tests are shown in Table 7.

4.3 Ordered logistic regression

In this study, ordered logistic regression was used to analyze the influence of the above factors on rural residents' satisfaction with post-disaster reconstruction. Two models were fitted in this study. Model one contained all of the above variables, while model two was obtained by re-fitting after deleting nonsignificant variables from model 1. The results is models one and two are shown in Table 7. The -2log-likelihood values are 1360.778 and 1178.072, respectively, while both of their Sig. values were 0.000, which means that model two fit the data better. Finally, model two was selected to interpret and analyze the data. Meanwhile, the Cox and Snell and Nagelkerke R^2 values were 0.315 and 0.335, respectively, which means that the model fit the data well and had statistical significance.

4.3.1 The influence of demographic variables on post-disaster reconstruction satisfaction

Villagers' understanding of post-disaster reconstruction methods (B = 0.223, p = 0.012) had a positive and significant influence on their overall level of satisfaction at a significance level of 5%; that is, the more fully rural residents understood reconstruction methods in

TABLE 6 Molecular results of exploratory factors.

Common factor	Variable	Load	
X1 The village committee acts as	F1	Subsidy guarantee	0.444
	F2	Information channel	0.594
	F3	Education and publicity about disaster prevention and mitigation	0.829
	F4	Reconstruction policy propaganda	0.835
	F5	Reconstruction decision-making participation	0.711
X2 Housing construction quality	F6	Type of layout of apartment	0.641
	F7	House safety	0.693
	F8	Quality of building materials	0.865
	F9	Technology of constructors	0.832
	F10	Reconstruction duration	0.538
X3 Public services	F11	Drinking water quality	0.798
	F12	Water convenience	0.871
	F13	Power supply demand	0.845
	F14	Communication requirements	0.742
— ——	F15	Planting space around housing	—
X4 Policy of benefiting farmers	F16	Cultivated land distance	0.629
	F17	Land reclamation	0.758
	F18	Agricultural training	0.779
	F19	Agricultural diversification	0.67
	F20	Non-agricultural industry introduction	0.507
X5 Cultural environment	F21	Talent education	0.527
	F22	Policies and systems	0.731
	F23	Cultural tradition	0.736
X6 Hardware environment	F24	Earthquake shelter	0.512
	F25	Road planning	0.846
	F26	Road quality	0.799
	F27	Sanitary environment/village appearance	0.456
	F28	Natural environment	0.469

residential areas, the higher their satisfaction level. Whether the residents had experienced a secondary earthquake disaster (B = -0.411, p = 0.053) was negatively correlated with their overall satisfaction at the 10% significance level, indicating that residents who had not experienced an earthquake disaster in the current reconstructed residential area had a high level of satisfaction with the reconstructed residential area. Indirectly explain the importance of reconstruction of residential areas in avoiding secondary earthquake disasters.

In addition, the change in annual household income before and after post-disaster reconstruction (B = -0.217, p = 0.057) had a negative correlation with overall satisfaction at a significance level of 10%. This option in the questionnaire of this study is designed as (significant increase = 1, some increase = 2, no change = 3, some decrease = 4, significant decrease = 5), that is, the annual household income after resettlement is higher. This is consistent with the findings of Shi et al. (2018) when they studied urban–rural migration and resettlement and found that increased income had a positive correlation with residents' life satisfaction.

4.3.2 The influence of six common factors on satisfaction

The more satisfied the villagers in the post-disaster reconstruction area were with the village committee's actions (X1,B = 0.525, p = 0.000) during the post-earthquake resettlement process, the higher their level of satisfaction with the post-disaster reconstruction of residential areas. The implementation of government policies is directly related to the style and ability of village cadres, which shows that improving these cadres' sense of responsibility and their ability is an important part of improving rural residents' satisfaction with the post-disaster reconstruction of residential areas. Huang et al. (2020) believed that village cadres should improve their own skills, use information to improve the efficiency of rural community governance, and achieve the goal of rural governance informatization. The more stable a cadre's network is, the higher the rural residents' evaluation of village cadres will be.

The quality of housing construction (X2, B = 0.434, p = 0.000) significantly affected villagers' overall satisfaction with post-disaster reconstruction. The better the quality of housing construction in post-disaster reconstruction areas, the higher the overall satisfaction of villagers with the post-disaster reconstruction. This shows that good earthquake-resistance and the comfort of the house itself are an important factor that determines rural residents' satisfaction with the post-disaster reconstruction of residential areas. Xiao et al. (2014) found that in the built environment, the greater the degree of

TABLE 7 Ordered logistic regression results of villagers' satisfaction.

Variable	Model 1		Model 2		Collinearity test	
	B	*p*-value	B	*p*-value	Tolerance	VIF
Gender	−0.208	0.237	—	—	—	—
Age	−0.004	0.573	—	—	0.562	1.778
Education level	−0.004	0.959	—	—	0.554	1.804
Is the current place of residence the birthplace?	−0.255	0.195	—	—	0.952	1.050
Participate in the reconstruction decision-making process?	−0.035	0.846	—	—	0.887	1.128
Have you received education on disaster prevention and mitigation?	−0.081	0.658	—	—	0.870	1.150
Have you experienced secondary disasters after the earthquake?	−0.360	0.106	−0.411*	0.053	0.887	1.127
Understanding of post-disaster reconstruction management regulations	0.138	0.244	—	—	0.518	1.930
Understanding of seismic fortification level of buildings	−0.137	0.272	—	—	0.478	2.094
Understanding of post-disaster reconstruction methods	0.212*	0.051	0.223**	0.012	0.623	1.604
Was the rebuilt house completed on time?	−0.341	0.124	—	—	0.937	1.068
Post-disaster reconstruction mode of housing is overall construction	0.018	0.935	—	—	0.854	1.171
Annual income of families after resettlement	0.024	0.316	—	—	0.946	1.057
Family income stability after resettlement	−0.049	0.783	—	—	0.942	1.062
Changes in annual household income before and after resettlement	−0.226*	0.052	−0.217*	0.057	0.937	1.067
X1 The village committee acts as	0.548***	0.000	0.525***	0.000	0.979	1.021
X2 Housing construction quality	0.447***	0.000	0.434***	0.000	0.973	1.028
X3 Public services	0.365***	0.000	0.372***	0.000	0.955	1.047
X4 Preferential agricultural policy	0.393***	0.000	0.393***	0.000	0.950	1.052
X5 Cultural environment	0.595***	0.000	0.594***	0.000	0.950	1.053
X6 Hardware environment	0.649***	0.000	0.637***	0.000	0.982	1.018

*, **, *** represent significance levels of 10%, 5%, and 1%, respectively.

completion of residential reconstruction and the shorter the construction period, the more satisfied disaster-affected people are with the post-disaster reconstruction. Therefore, the quality and efficiency of housing construction in a post-disaster reconstruction area play an important role in improving villagers' satisfaction with post-disaster reconstruction.

The public services in the post-disaster reconstruction area (X3, B = 0.372, $p = 0.000$) had a significant positive correlation with the villagers' overall satisfaction with post-disaster reconstruction, which showed that rural residents pay attention to the level of public services at resettlement sites. The higher the level of public services, the higher the rural residents' satisfaction with the post-disaster reconstruction settlements (Wang and Li, 2019). In a study of rural medical and health services, Wang and Li (2019) found that rural residents with better self-rated health status were more satisfied with public health services and that the higher the satisfaction of rural residents with medical and health services, the higher their life satisfaction. Therefore, in the process of post-disaster reconstruction, not only should the construction work be done well but also the role of public services should not be ignored.

Preferential agricultural policies (X4, B = 0.393, $p = 0.000$) had a significant positive impact on villagers' overall satisfaction with the post-disaster reconstruction area, indicating that the greater the implementation of preferential agricultural policies, the higher the villagers' overall satisfaction with post-disaster reconstruction settlements. This is consistent with the view of Tian and Zhao (2010), that the intensity of implementation of agricultural benefit policies and the two exemption and one subsidy policies can have a great and positive impact on farmers' life satisfaction.

The higher the level of satisfaction of residents with the construction of the human environment (X5, B = 0.594, $p = 0.000$) in the post-earthquake reconstruction area, the higher the overall satisfaction of villagers with the post-earthquake reconstruction residential area. This showed that improving rural residents' satisfaction from the perspective of rural policy environment, rural talent environment, and rural cultural environment will be conducive to improving rural residents' satisfaction with post-disaster reconstruction settlements. Ye (2015) suggested that there are many problems in the construction of the rural cultural environment, which reduce the happiness of rural residents to varying degrees. They proposed that corresponding policies should be formulated for different problems, to improve the life satisfaction of rural residents (Ye, 2015), which is consistent with the conclusion of this study.

The higher the villagers' recognition in the construction of hardware environment (X6, B = 0.637, p = 0.000), the higher the villagers' overall satisfaction with the post-disaster reconstruction, and the greatest influence of hardware facilities construction in the post-disaster reconstruction area. This shows that the construction of infrastructure for post-disaster reconstruction settlements is the most important content that affects rural residents' satisfaction with these settlements. Routes for rapid evacuation and earthquake shelters are basic requirements necessary to improve the level of seismic resilience in the new era. The timeliness of evacuation routes and the reliability of earthquake shelters during disasters will reduce casualties. Therefore, rational road planning and the safety and accessibility of earthquake shelters had a significant impact on rural residents' satisfaction with the rebuilding of settlements after a disaster, which is consistent with the conclusions of a study by Ma et al. (2021).

5 Conclusion

Rural residents' overall satisfaction with the post-disaster reconstruction of residential areas is influenced by many factors. Based on a literature search, combined with information about the current situation in ten post-disaster reconstruction settlements in Sichuan Province, this study summarized the factors that affect rural residents' overall satisfaction with post-disaster reconstruction settlements. In this questionnaire survey, 483 valid questionnaires were collected following face-to-face completion of the questionnaires by village residents. This research uncovered the following insights:

1) The more the villagers in earthquake-stricken areas know about post-disaster reconstruction methods, the greater their overall level of satisfaction with post-disaster reconstruction. Therefore, attention should be paid to improving rural residents' awareness of methods used to reconstruct residential areas and strengthening the publicity and education around post-disaster reconstruction methods.
2) Following earthquake disaster reconstruction, if annual household income increases to more than that before the reconstruction, the villagers in the disaster area will be more satisfied with the overall reconstruction. Therefore, we should pay attention to employment issues following reconstruction and increase the income of rural residents after a disaster.
3) Six public factors, such as the village committee acts as, housing construction quality, public service, policy of benefits for farmers, cultural environment, and hardware environment, all significantly positively affect residents' overall satisfaction with post-earthquake reconstruction. This study is of great importance for enriching the theory of residents' satisfaction and the practice of post-earthquake reconstruction.

Through the post-earthquake reconstruction of Wenchuan residential satisfaction survey, this research has revealed the influence of rural residents for post-earthquake reconstruction overall satisfaction of the key factors of residential area, reveals the relationship between human activities and residents of the ecological environment. It also reveals the unreasonable planning in the construction of post-disaster reconstruction settlements from the perspective of rural residents, complements the theory development of post-disaster reconstruction settlement. More scientifically, this research describes the construction status and problems of post-disaster reconstruction settlements. This has practical significance for maintaining the spatial stability of post-disaster reconstruction settlements.

6 Limitations

Despite the innovative essence and significant findings of this research, this study does have some limitations, as elaborated below.

1) The variables collected were limited. Although this study combined the current situation in post-disaster reconstruction settlements and put forward a variety of factors based on existing research, the content cannot fully cover all aspects of rural residents' satisfaction with post-disaster reconstruction settlements. Therefore, there are limitations due to the variables collected in this study.
2) Data values are limited. When respondents are satisfied with each indicator, their understanding of the questions set in the questionnaire may have been biased due to their own educational level and mood at the time, so the data value has certain limitations. In future research, the formulation of the questionnaire should take this objective phenomenon into account, and the language should be as concise as possible, easy to understand, and avoid any redundancy.
3) The scope of the investigation also had limitations. This study selected rural residents from ten sample villages in Sichuan Province as the research objects, and the survey was conducted in the form of on-site household visits, so it was difficult to avoid contingency and regional distribution limitations. In future research, it will be necessary to increase the number of areas investigated to make the spatial distribution more representative.

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 were not required for the study involving human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization: YA, LH; data collection and analysis: LH, JZ, ZZ; writing the original draft: JZ, ZZ, TW, YW, YA; revising: TW, YC; resources: YA, TW; supervision: YA, TW, YC.

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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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How green credit policy shapes financial performance: Evidence from Chinese listed construction energy-saving enterprise

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This study uses the introduction of the Green Credit Guidelines in 2012 as a quasi-natural experiment. We selected Chinese A-share listed enterprises from 2004 to 2020 as the sample and applied PSM-DID to examine the impact of green credit policy on the performance of construction energy-saving enterprises. The study revealed that: 1) green credit policy has a significant contribution to the performance of construction energy-saving enterprises. In addition, it still holds after the robustness tests (replacing the PSM matching method and adding or subtracting the two methods of control variables) and the placebo test. 2) A positive correlation between the performance of construction energy-saving enterprises and short-term debt. Meanwhile, short-term debt is a mediating variable between green credit policy and the performance of construction energy-saving enterprises. 3) The impact of green credit policy on the performance of non-state-owned (non-SOEs) is more pronounced compared to state-owned (SOEs). This study reveals the micro effects of green credit policy from the perspective of the performance of construction energy-saving enterprises. It not only helps to understand the economic effects of green credit policy, but also provides corresponding insights for the subsequent promotion of green credit policy and construction energy-saving enterprise development systems.

KEYWORDS

green credit policy, construction energy-saving enterprises, financial performance, PSM-DID, meditating effect

1 Introduction

Increasing global industrialization and over-exploitation of natural resources have caused environmental degradation issues (Chen L et al., 2022). In response to resource depletion and ecological disruption, 124 countries worldwide have, as of February 2021, declared their intention to become carbon neutral and achieve net-zero carbon emissions by 2050 or 2060 (Chen, 2021). In 2020, China proposed, at the 75th United Nations General Assembly, that it would adopt effective policies and measures to reach the carbon peak by 2030 and strive to achieve the national goal of carbon neutrality by 2060. The 2021 Global Status Report for Buildings and Construction showed that the construction sector accounted for 36% of global final energy consumption and 37% of energy-related CO_2 emissions (Global CCS Institute, 2021). A fast-growing building boom in emerging countries makes this environmental problem even more challenging (Wang et al., 2018).

To meet future carbon emission management targets, except technical means, we also need to manage the financing and transaction costs of projects that are aligned to sustainable development goals (Kumar et al., 2022). This is known as sustainable finance, which is a finance tool that contributes to sustainability (Aizawa and Yang, 2010). As an important element of the sustainable financial system (Lian et al., 2022), China announced its green credit policy in 2007. The introduction of "green credit" has raised the threshold for loans to enterprises. Compliance with environmental testing standards, pollution control effectiveness, and ecological protection are important prerequisites for credit approval. It is to be used to curb the blind expansion of high-pollution and high-consumption industries. The China Banking Regulatory Commission issued the Green Credit Guidelines (GCGs) in 2012, calling on Chinese banks to provide credit to enterprises that emit pollutants or gobble up energy and natural resources to extend credit on preferential terms for green projects (Aizawa and Yang, 2010; Tan et al., 2022).

Debt financing from banks remains the most important source of external financing for research and development activities by enterprises in developing countries (Ayyagari et al., 2011; Liu et al., 2021). The green credit policy guides the green transformation of enterprises through capital allocation (reducing the scale of debt financing and increasing the cost of debt) for heavily polluting enterprises (Liu et al., 2021). But for environmentally friendly construction energy-saving enterprises, green credit policy is an even more superior demonstration of rapid financial performance improvement. In terms of the reallocation of credit resources, the introduction of green credit policy may increase the scale of debt financing and reduce the cost of debt, resulting in an improved capital investment structure and financial performance of construction energy-saving enterprises. In terms of policy practice, green credit policy priorities the provision of credit resources to enterprises with environmental performance, while avoiding credit support to enterprises with high environmental risks, thereby internalizing the external environmental costs of enterprises. Hence, green credit policy has to some extent facilitated the possibility of construction energy-saving enterprises financing for environmentally friendly constructions (Ghisetti et al., 2017; Wang E et al., 2019).

Previous studies on green credit have mainly focused on the manufacturing sector due to its heavy pollution (Liu et al., 2017; Sun et al., 2019), while few studies have been conducted on green credit in the construction sector. The construction sector has not yet undergone a real structural transformation, and its carbon emissions will continue to rise and contribute to climate warming. Green credit can improve the efficiency of resource allocation, continuously promote the advancement of the industrial structure, and rationalization of the industrial structure (Zhu, 2022). At the same time, the introduction of green credit policy can also encourage construction enterprises to actively improve environment protection and energy-efficiency technologies, thus efficiently solving the problem of environmental pollution (Hu et al., 2022).

In summary, only a few studies are exploring green credit policy in the construction sector. Thus, the introduction of green credit policy in the construction sector needed to be studied. Chinese enterprises always fail to take active environmental protection measures (Zhang et al., 2021). Moreover, the policy introduction is weak and the system needs to be improved in China (Kong et al., 2020). To address these issues, this study assesses the impact of green credit policy on the financial performance of construction energy-saving enterprises using secondary data on construction energy-saving enterprises in China. Furthermore, short-term debt and long-term debt may be key factors in the influencing mechanism of green credit policies on enterprises' financial performance (Liu and Luo, 2019). Thus, the current study explores the following two research questions (RQ):

RQ1: In the context of the construction sector, what is the relationship between green credit policy and the financial performance of construction energy-saving enterprises?

RQ2: How do short-term debt and long-term debt mediate this relationship?

This study explores how green credit policy influences the financial performance of construction energy-saving enterprises, while also considering the mediating effect of short-term debt and long-term debt and the moderation effect of controlling shareholders. Overall, this study makes four main contributions. Firstly, this study sampled listed construction energy-saving enterprises, contributing to the existing green credit policy-financial performance relationship literature by extending the research scope to the construction industry. Our results provide implications for the sustainable development of the construction industry. Secondly, the PSM-DID method was applied to non-random data and avoided the occurrence of sample selectivity bias and heterogeneity. It effectively makes the DID method satisfy the common trend. Thirdly, this study enriches the environmental economic research of construction enterprises by revealing how the short-term debt and long-term debt shape this green credit policy-financial performance relationship. Finally, this study can instruct the government, banks and enterprises to improve the green credit policy. The results guide policy initiatives and enterprises' strategies targeted toward promoting the environmental efforts of construction enterprises and ultimately facilitating the achievement of the goal of carbon neutrality. The rest of this study is structured as follows. First, the study describes the theoretical foundation and research hypotheses. Then, the study reports the research methods and data analyses. The study closes with the implications and conclusions.

2 Theoretical foundation and research hypotheses

2.1 Stakeholder theory

Stakeholder theory shows that the pressure of implementing green credit may help enterprises ease the conflict between them and stakeholders, and achieve more healthy and sustainable development (Kitsikopoulos et al., 2018). The stakeholder theory dates back to 1932 and was proposed by E. Merrick Dodd. In 1963, the Stanford Research Institute (SRI) first proposed the concept of "stakeholders". Stakeholder theory means that enterprises should consider the interests of other stakeholders in their daily operations, not only the interests of shareholders. Among them, stakeholders include employees, consumers and, above all, the community as a whole (Dodd, 1932).

As the environment deteriorates, public awareness of environmental and local ethnic issues is growing. This has led to the demand that corporations engage in socially desirable actions to establish congruence between corporate decision-making and social values (Baldini et al., 2018). Green credit policy is one of the means by which the government cooperates with financial institutions to urge enterprises to attach importance to energy conservation, environmental protection and green development through credit channels (Zhang et al., 2011). Referring to stakeholder theory, green credit's implementation helps to alleviate the contradiction between enterprises and stakeholders, which can help them achieve more healthy and steady development (He et al., 2019b).

2.2 Signaling theory

In addition, the signaling theory shows that environmental regulation may encourage enterprises to standardize their behaviors, to transmit favorable signals to the public (Yu et al., 2017). In the financial market, due to the objective existence of information asymmetry, enterprises release the "signal" to the market by improving an enterprise's environmental performance and social reputation, which leads to a reduction in the information asymmetry between an enterprise and its external stakeholders (Lys et al., 2015; García-Sánchez et al., 2020; Khan et al., 2021). Therefore, according to the lending targets and lending standards of green credit policy, enterprises that send a "green" signal to banks and the public can obtain more financing opportunities and reduce their financing costs. As a result, financial performance increases (Saeidi et al., 2015; Ren et al., 2020).

2.3 Green credit

Green credit is a means whereby financial institutions achieve sustainable economic and social development. It includes policies, institutional arrangements, and practices that promote environmental improvements and energy conservation through credit instruments (Lian et al., 2022). Green credit originated from the Equator Principles and is referred to as the international green credit policy (Aizawa and Yang, 2010), which is a voluntary agreement to mitigate environmental consequences and fulfill corporate social responsibility (Conley and Williams, 2011). Although not legally binding, the Equator Principles have gradually become the sector standard for financial institutions in practice, and the basic bottom line for green credit operations internationally (Lian et al., 2022).

Many studies have investigated green credit and environmental protection, business operations, and industrial structure (Hong et al., 2021; Hu et al., 2022; Li et al., 2022). For example, Liu et al. (2021) studied the relationship between green credit policy and enterprises' green technology innovation performance. Lyu et al. (2022) explored the impact and mechanism of green credit policy on carbon emissions at the national and regional levels. Lai et al. (2022) discussed the impact of green credit on new energy enterprises' value. Zhu (2022) analyzed the impact of green credit and technological innovation on industrial structure upgrading.

2.4 Green credit and enterprises' financial performance

Many studies have shown a direct correlation between green credit and economic performance (e.g., enterprises' financial performance and value) (Yao et al., 2021; Lai et al., 2022; Lian et al., 2022; Xi et al., 2022). Green credit policy will have a "penalty effect" on the financial performance of highly polluting enterprises and have a positive impact on the value of environmentally friendly enterprises (Yao et al., 2021; Lai et al., 2022).

The GCGs strategically set out more specific and clear requirements for financial institutions, including banks. The guidelines require banks and other financial institutions to implement green credit policy more effectively and to make every effort to promote energy conservation, emission reduction, and environmental protection (Lian et al., 2022). For example, commercial banks strictly control the threshold of credit approval by following guidelines and making the environmental performance of enterprises an important factor in credit approval. This is manifested in the form of loan support, or preferential interest rate loans, to environmentally friendly enterprises or green projects (Aizawa and Yang, 2010). In this way, construction energy-saving enterprises provide benefits and convenience, as well as achieve economic growth and environmental protection (Lai et al., 2022). This leads to the following hypothesis:

H1: Green credit policy has improved the financial performance of construction energy-saving enterprises compared to non-construction energy-saving enterprises.

2.5 Mediating effect of short-term debt and long-term debt

The process by which credit policy affects an enterprise can be described in the following way: Financial institutions influence the cash flow of enterprises through credit channels to manage their investments. This further affects the cash flow structure of enterprises, which ultimately changes the capital structure and the allocation structure of the factors of production. Consequently, the production and operation of enterprises will be greatly affected (Majumdar and Chhibber, 1999; Pisicoli and Bencivelli, 2021). In addition, enterprises with higher debt can reduce agency costs and lower value-free investments. According to static equilibrium theory, it is known that a lower corporate debt ratio leads to a lower corporate value. In turn, corporate value is closely linked to total corporate profits and return on net assets (Modigliani and Miller, 1958). When the corporate value is higher, enterprises can establish a good image of sound corporate operations as well as a greater public trust, which will lead to greater popularity of their products, which will result in increased corporate financial performance (Ioannou and Serafeim, 2012; Wang et al., 2022). Green credit policy can influence the borrowing ability and financing cost of enterprises (He et al., 2019a). The GCGs require banks to deny credit to enterprises with non-compliant environmental and social performance. From the perspective of signaling theory, financial institutions will provide preferential interest rates to eco-friendly enterprises to promote the development of environmental protection industries. Under the requirements of this policy, if commercial banks strictly control credit by policy requirements, heavily polluting enterprises with high environmental risks will be impacted by green credit policy and face debt financing dilemmas. Therefore, their debt financing scale, cost, and maturity will be constrained (Li et al., 2022). The construction energy-saving enterprises will receive preferential financing, which is propitious to enterprises' financial performance and leads to the following hypotheses:

H2a: Green credit policy has a positive influence on the short-term debt of construction energy-saving enterprises.

H2b: Green credit policy has a positive influence on the long-term debt of construction energy-saving enterprises.

H3a: The financial performance of construction energy-saving enterprises is positively correlated with short-term debt.

H3b: The financial performance of construction energy-saving enterprises is positively correlated with long-term debt.

2.6 The heterogeneity of the effect of green credit policy on enterprises' financial performance

Based on the type of controlling shareholders, the ownership of listed enterprises is typically classified into state-owned (SOEs) and non-state-owned (non-SOEs) (Kim et al., 2019). The proportion of the SOEs equity indicates the relationship between political factors and enterprises. SOEs have a natural political gene, and it is normal for the SOEs to have political connections and cooperate with the government (Cheng et al., 2017). Governments in China possess considerable control over the allocation of resources through their control of the SOEs. The development trend of SOEs is guided by the government's policies and shares interests with the government. Therefore, the SOEs will more actively respond to the call of national policies, adhere to the concept of sustainable development and the scientific outlook on development, and make due contributions to environmental protection. Overall, enterprises with high political connections take a more active part in responding to the government's environmental appeals (Li et al., 2022). In this way, SOEs tend to choose projects related to energy conservation and environmental protection because green credit policy provides favorable opportunities for them. This leads to the following hypotheses:

H4: Compared with non-SOEs, the impact of green credit policy on the financial performance of SOEs is more obvious.

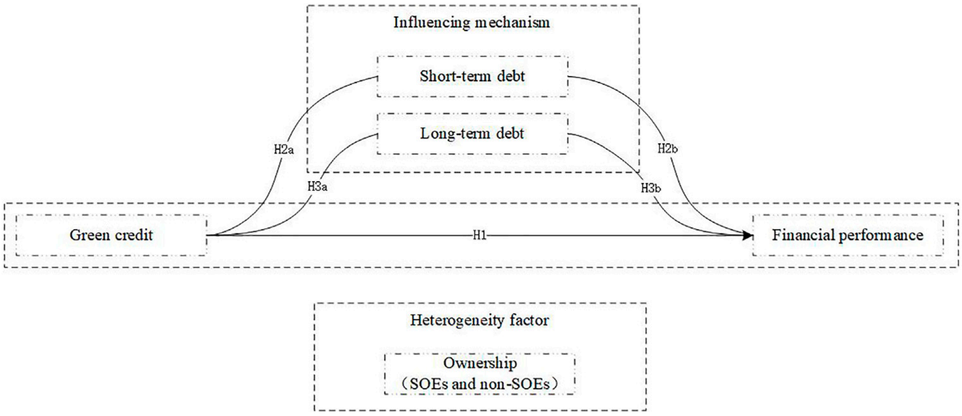

FIGURE 1
Logical diagram of the relationship between green credit and financial performance.

3 Materials and methods

3.1 Sample and data sources

We used the A-share listed enterprises in China from 2004 to 2020 as a research sample. In 2012, the GCGs were introduced. Hence, we chose 2012 as the midpoint of this period and collected data for 8 years before and after. The reason for choosing data for the 8 years before and after is that the data of enterprises in the China Stock Market and Accounting Research (CSMAR)[1] (http://cndata1.csmar.com/) database ends in March 2022. However, there is a large amount of missing annual data for 2021. Thus, we finally set the study period as 2004–2020. We used construction energy-saving enterprises as the treatment group and other enterprises as the control group. Construction energy-saving enterprises are defined by keywords ("Environmental Energy," "Green Construction," and "Construction Energy Efficiency") searched through enterprise attributes in the Flush database[2] (https://www.10jqka.com.cn/). We searched for a total of 166 construction energy-saving enterprises. Regarding the processing of the full sample, this study refers to the method used by Feenstra et al. (2014) to process the data. The data to be excluded are: ST listed enterprises and *ST listed enterprises; enterprises with integrated industries in the National Economic Classification; enterprises with vacant industry codes; and enterprises with selected variables less than or equal to 0. Finally, we obtain 15,093 observations from 1,022 listed enterprises for the full sample, of which the treatment group contains 10,019 and the control group contains 14,074.

3.2 Variable description

3.2.1 Dependent variable

The ROTA has been used extensively in previous studies (Binti Mohamad et al., 2017; Nguyen et al., 2021), and represents the ratio of total net profit to average total assets. It is primarily used to measure an enterprise's ability to earn profits from its assets by reflecting the efficiency of utilizing total assets (Janicka and Sajnog, 2021). The higher this ratio is, the more profitable the total assets are (Janicka and Sajnog, 2021). In addition, the classification of the enterprise is based on fixed assets, which rely more on accounts payable that finance their total turnover. Therefore, ROTA can reflect the financial performance of an enterprise to a certain extent.

3.2.2 Independent variables

Since the GCGs were introduced in 2012, in this study the dummy variables Treated and Time are used to distinguish the four subcategories. Where Treated = 1 represents construction energy-saving enterprises, Treated = 0 represents non-construction energy-saving enterprises, Time = 1 represents the year after the introduction of green credit policy, and Time = 0 represents before the implementation of green credit policy.

3.2.3 Mediating variables

The enterprise's debt refers to a present obligation arising from past transactions or events that are expected to result in an outflow of economic benefits. The level of debt of an enterprise is

1 CSMAR database is a research-oriented and accurate database in economic and financial field developed by Shenzhen Sigma Data Technology Co., Ltd. The data began in 1998 and has been continuously updated.

2 Flush database is the largest stock trading database in China.

TABLE 1 Variable setting and descriptive statistics.

Variable type	Variable name	Assignment rules	Obs	Mean	SD	Min	Max
Dependent variable	ROTA	Return on total assets	15,093	0.0346	0.0691	−3.164	0.786
	Time × Treated	An interaction term for the time dummy variable and a grouping dummy variable	15,093	0.0349	0.183	0	1
Independent variable	Time	0 for 2012, 1 for 2012 and beyond (including 2012)	15,093	0.525	0.499	0	1
	Treated	Construction energy-saving enterprises = 1	15,093	0.0675	0.251	0	1
		Non-construction energy-saving enterprises = 0					
Mediating variable	Shortdebt	Short-term debt	14,807	1,506.45	4,360.13	0	166,688
	Longdebt	Long-term debt	14,807	1740.43	8,144.08	0	207,160.4
	Ret	Stock returns	15,093	0.385	0.974	−6.464	44.36
	Lr	Liquid ratio	15,091	4.389	71.63	0	7,507
	Np	Enterprise total profit growth ratio	13,299	0.298	50.98	−1,503	2,287
	Age	Enterprise age	15,006	306,739	321,085	103	1,037,044
Control variable	Lev	Enterprise liabilities to assets (L/A) ratio	15,093	0.415	0.209	0	2.008
	Tato	Enterprise total asset turnover ratio	14,786	0.449	0.551	−0.0086	22.33
	Profit	Enterprise growth rate of net profit	13,163	−1.185	71.28	−4,542	3,240
	Revenue	Enterprise operating growth ratio	15,091	0.769	17.31	−3.781	1,570
	State	Controlling shareholders	14,649	1.859	0.939	1	8
	Tq	Tobin's q	14,913	1.808	1.280	0.688	28.30
Robust analysis substitution variables	Size	Logarithm of the enterprise's total assets	14,889	161.4	627.1	0.6	19,000
	Roe	Enterprise return on equity	15,073	0.0340	0.845	−53.96	4.248

Note: Obs, observation; SD, standard deviation.

critical to its earnings and value (Yazdanfar and Öhman, 2015). Therefore, based on the availability of data, this study will examine the effect mechanism of green credit policy on the financial performance of construction energy-saving enterprises from short-term and long-term debts.

3.2.4 Control variables

To solve the bias problems that may be caused by the omission of variables in the equation of the model, as much as possible, this study controls the effects of these variables. Ten control variables are selected: stock returns (Ret) (Wang G et al., 2021), liquid ratio (Lr) (Zhang et al., 2015), enterprise total profit growth ratio (Np) (Huo and Zhang, 2017), enterprise age (Age) (Carnahan et al., 2010), enterprise liabilities to assets (L/A) ratio (Lev) (Díaz-Fernández et al., 2015), enterprise total asset turnover ratio (Tato) (Edward and Marciano, 2019), the enterprise growth rate of net profit (Profit) (Gao et al., 2021), enterprise operating growth ratio (Revenue) (Fu and Shen, 2020), equity nature (State) (Li, 2011), and Tobin's q (Tq) (Lee et al., 2021) as control variables, and selects assets scale (Size) (Goll et al., 2008) and return on equity (Roe) (He et al., 2020) as replacement variables for the robustness test. Ret, Lr, Np, Lev, Tato, Profit, Revenue, Tq, Roe are collected from the financial annual reports of the enterprises. As important financial indicators, they are closely related to the financial performance of the enterprises (Azeez, 2015). The enterprise age is measured as the reporting period minus the number of years that the enterprise has been in the market (measured in months). Younger enterprises tend to be aggressive and innovative, while older enterprises usually experience organizational rigidity and reduced efficiency (Loderer and Waelchli, 2011; Edward and Marciano, 2019). Thus, enterprise age may affect financial performance by influencing the strategic decisions of the enterprise. The equity nature, with its unique flexibility, is the preferred way for controlling shareholders to alleviate financing constraints, and largely affects enterprises' financial performance (Ren et al., 2022). Enterprise size is measured as the natural logarithm of the enterprise's total assets at the end of the year. Smaller enterprises focus more on operations, while larger enterprises focus on strategy. Two different directions of development can have an impact on the financial performance of both over time (Laitinen and Kadak, 2018). The assignment rules of each variable and descriptive statistics are shown in Table 1.

3.3 Model specification

In the field of policy effect evaluation, the Differences in Differences (DID) method based on "quasi-natural experiments" is the most widely used research tool in recent years (Wang H et al., 2019; Chen et al., 2021; Fu et al., 2021; Zhang and Wang, 2021). As a purely exogenous event, the GCG satisfies the basic characteristics and assumptions of a quasi-natural experiment as not occurring for experimental purposes, and not influenced by individual companies (Withers and Li, 2021). Though the presence of other unobservable factors (individual fixed effects and environmental effects) may lead to less accurate policy assessment results, DID can exclude the effect of unobservable factors by taking the difference in results before and after policy introduction (Wang Z et al., 2021; Khan et al., 2022). Specifically, by comparing the differences in the effects of events on the treatment and control groups, the effects of other interfering causal factors or omitted variables can be overcome, allowing for better identification of causal relationships.

The essence of exploring the impact of green credit policy on the financial performance of construction energy-saving enterprises is to reveal the differences in the enterprises' financial performance before and after the trial period. However, the most important premise of using the DID model is that the treatment and control groups must satisfy the common trend, i.e., in the absence of the GCGs, the financial performance of construction energy-saving enterprises and non-construction energy-saving enterprises will move in the same direction. Inconsistencies between treatment and control groups in sample selection methods or sample classification criteria are likely to lead to different trends. The PSM-DID method, proposed and developed by Heckman et al. (1997) can effectively make the DID method satisfy the common trend. PSM method is matched to the treatment and control groups, i.e., enterprises are found in the control group that is as consistent as possible with observable variables in the treatment group. Therefore, this study used construction energy-saving enterprises as the treatment group and non-construction energy-saving enterprises as the control group.

Subsequently, this study divides the sample of listed companies into four subsamples, i.e., the treatment group before and after the introduction of green credit policy and the control group before and after accordingly. The regression model is set up as follows. To test H1 and H4, if the coefficient is significantly positive, then green credit policy is likely to increase the financial performance of construction energy-saving enterprises, and H1 and H4 are valid.

$$ROTA = \beta_0 + \beta_1 Time + \beta_2 Treated + \beta_3 Time \times Treated + \beta_4 Controls + Enterprise + Year + \varepsilon \quad (1)$$

To investigate the impact of green credit policy on enterprises by controlling for their bank credit status, this study refers to Sun et al. (2019) and Wu et al. (2022) to try out the mediation effect. We explored the mechanism of the impact of green credit policy on enterprises' financial performance in terms of both short-term and long-term debts and constructed the following mediation effect model.

$$Shortdebt_{it} = \beta_0 + \beta_5 Time \times Treated + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (2)$$

TABLE 2 The PSM results.

	Unmatched	Matched	Total
Treatment group	0	11,772	11,772
Control group	0	394	394
Total	0	12,166	12,166

$$ROTA_{it} = \beta_0 + \beta_6 Time \times Treated + \theta_1 Shortdebt + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

$$Longdebt_{it} = \beta_0 + \beta_7 Time \times Treated + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (4)$$

$$ROTA_{it} = \beta_0 + \beta_8 Time \times Treated + \theta_2 Longdebt + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (5)$$

Models (2) and (3) are constructed to test for H2a and H3a. If the coefficients are significantly positive, then green credit policy affects construction energy-saving enterprises' financial performance by influencing short-term debt. Models (4) and (5) are constructed to test H2b and H3b. If the coefficients are significantly positive, then long-term debt plays a partially mediating role in influencing green credit policy for construction energy-saving enterprises.

4 Results

4.1 Empirical analysis

4.1.1 Propensity score matching results and balance test

The PSM can be used to correct for bias in the estimates of intervention effects (Grose et al., 2020; Maina et al., 2020). It allows treatment and control groups to compare the differences in their estimates under conditions that are as similar as possible (Heinze and Jüni, 2011; Dong and Lipsey, 2018). Considering that the number of observations in the control group was much larger than the treatment group, this study used a 1:4 nearest neighbor matching method and was analyzed using Stata16 through a logit model. Table 2 depicts the PSM results after sample matching. The results showed that there was a good matching effect (not unmatched in both the treatment and control groups) (Stuart, 2010; Naz et al., 2018). To ensure that propensity scores between the treatment and control groups are not significantly different and to overcome the effect of selectivity bias, a balance test needs to be performed on the matched sample data (Heo et al., 2017; Fan and Zhang, 2021). Table 3 depicts the logit regression results and the balance test results. From Rosenbaum and Runim (1983), it is known that the

TABLE 3 Logit regression results and balance test results.

Variable name	Unmatched	Mean		%Reduct		$p > \|t\|$
	Matched	Treated	Control	%Bias	|bias|	
Ret	U	0.5394	0.46452	7.9	23.2	0.129
	M	0.5394	0.48191	6.0		0.348
Lr	U	1.8949	3.05	−8.2	94.2	0.244
	M	1.8949	1.8284	0.5		0.755
Np	U	−1.5287	−0.24287	−3.6	85.5	0.455
	M	−1.5287	−1.7146	0.5		0.947
Age	U	3.3E + 05	3.0e + 05	8.7	73.6	0.096
	M	3.30E + 05	3.40e + 05	−2.3		0.753
Lev	U	0.44342	0.40549	19.2	69.4	0.000
	M	0.44342	0.45501	-5.9		0.407
Tato	U	0.59558	0.4532	23.5	55.6	0.000
	M	0.59558	0.53241	10.4		0.148
Profit	U	−0.48351	−0.75932	0.6	-240.5	0.932
	M	−0.48351	−1.4227	2.0		0.788
Revenue	U	0.34438	0.45008	−2.1	52.6	0.762
	M	0.34438	0.29424	1.0		0.717
State	U	1.9467	1.877	7.1	67.6	0.204
	M	1.9467	1.9693	−2.3		0.763
Tq	U	1.6494	1.7953	−12.7	69.4	0.019
	M	1.6494	1.5987	4.4		0.473

Note: U, unmatched; M, matched.

matching effect is achieved if the absolute value of the bias after matching is less than 20%. This study discovered that the absolute value of the bias of all variables after matching was less than 20%, and there was a significant reduction in the standard deviation of each variable after matching in the treatment and control groups. The above results indicate that the condition of the treatment and control groups are relatively close after PSM by the balance test.

4.1.2 The impact of green credit policy on enterprises' financial performance

According to the established model (1), the regression analysis was conducted on the full sample and PSM sample, as shown in Table 4. The first and second columns are regression results for the full sample. The coefficient of Time × Treated is 0.00385, which is non-significant at the 10% level when no control variables are included. Considering that there are potential relevant omitted variables, we added control variables. The regression results showed that the coefficient of Time × Treated is 0.00477, which is significantly positive at the 5% level. Therefore, our preliminary view is that the introduction of green credit policy can have a positive effect on the financial performance of construction energy-saving enterprises to some extent. The test under the full sample fails to accurately reflect the effect of the policy because enterprises may have significantly different variables and thus require a further regression analysis after the PSM method (Qin et al., 2020; Jia et al., 2021). The coefficients of Time × Treated are significantly positive at the 5% level (both without and with the inclusion of control variables), similar to the results of the full sample. In summary, the introduction of green credit policy makes the financial performance of construction energy-saving enterprises increase remarkably, and H1 is confirmed.

4.2 Robustness tests and placebo tests

4.2.1 Replacement PSM method

Existing studies of PSM-DID frequently use replacement PSM methods for robustness tests. The previous section used 1:4 nearest neighbor matching, so we re-matched the samples by caliper matching and kernel matching. Regression analysis results are listed in Table 5, which shows that the regression coefficient of Time × Treated was still significantly positive at the 10% level after changing the matching method, which was not significantly different from the

TABLE 4 A test of the impact of green credit policy on the financial performance of construction energy-saving enterprises.

Variable name	Full sample		PSM sample	
	No control variables	Control variables	No control variables	Control variables
Time × Treated	0.00385	0.00477**	0.0238***	0.0122**
	(0.00336)	(0.00230)	(0.00692)	(0.00491)
Time	0.00168	0.0000809	0.000219	−0.00573
	(0.00268)	(0.00191)	(0.00775)	(0.00422)
Treated	—	—	—	—
Ret		0.0236*		0.0323***
		(0.0128)		(0.00763)
Lr		−0.0000342		−0.000355
		(0.0000321)		(0.000518)
Np		0.000163**		0.000247***
		(0.0000711)		(8.97e-05)
Age		6.95e-09		2.01e-08*
		(1.25e-08)		(1.15e-08)
Lev		−0.0552***		−0.0687***
		(0.00575)		(0.0102)
Tato		0.0131***		0.0129***
		(0.00454)		4.80e-06
Profit		0.0000262		(1.78e-05)
		(0.0000177)		(0.0000210)
Revenue		−0.0000282		−0.000149
		(0.0000785)		(0.000569)
State		0.000617		0.00176*
		(0.000559)		(0.00102)
Tq		0.00698***		0.00911***
		(0.000835)		(0.00228)
Constant	0.0332***	0.0326***	0.0380***	0.0299***
	(0.00194)	(0.00708)	(0.00656)	(0.00878)
Enterprise	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Number of enterprises	1,022	1,018	775	775
R-squared	0.001	0.289	0.023	0.521

Note: standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

regression result of 1:4 nearest neighbor matching, thus the model (1) is robust.

4.2.2 Increase and decrease control variables

To fully test the robustness of the model, this study was also tested by replacing control variables. The impact of green credit policy on the financial performance of construction energy-saving enterprises is analyzed by replacing Np and Lr with Size and Roe in the control variables, and the regression results are shown in Table 6. Our findings indicate that the Time × Treated coefficient remained significantly positive at the 10% level with the inclusion of control variables. There is no substantial difference between this and the regression results in the previous section, which fully confirms the robustness of the model (1).

4.2.3 Placebo tests

The above study shows that the introduction of a green credit policy leads to a remarkable improvement in the financial performance of construction energy-saving enterprises. This study used the PSM-DID model to overcome the endogeneity between green credit policy and the financial performance of construction energy-saving enterprises (Dong and Zheng, 2022; Guo et al., 2022). The most disruptive to DID's evaluation of policy effects comes from one fact: The resulting impact may not be due to the green credit policy in this study, but is instead influenced by other policies or factors (Dong and Zheng, 2022; Guo et al., 2022). Typically, in studies using the PSM-DID model, a placebo test is utilized to test the robustness of the results (Fu et al., 2021). In Summary, to exclude the influence of random factors on the experiment and to improve the credibility of our conclusions, we used a placebo test to test the treatment results. Figure 2 reports the kernel density distribution of the estimated coefficients for the 500 randomly generated treatment groups. It shows the mean value of the regression coefficients is nearly 0, indicating that the change in the financial performance of construction energy-saving enterprises is indeed affected by the green credit policy.

4.3 Mechanism analysis

Short-term debt and long-term debt can be used to examine the mechanisms by which green credit policy affects the financial performance of construction energy-saving enterprises. Table 7 reports the results of the tests for the role of Shortdebt and Longdebt on ROTA. In particular, model (1) is the mediation effect test step one, which tests the effect of Time × Treated on ROTA. The results

TABLE 5 Caliper matching, kernel matching regression results.

Variable name	Caliper matching		Kernel matching	
	No control variables	Control variables	No control variables	Control variables
Time × Treated	0.00539*	0.00468*	0.00555*	0.00411*
	(0.00316)	(0.00259)	(0.00314)	(0.00234)
Time	−0.00132	−0.000123	−0.000898	−0.00116
	(0.00233)	(0.00190)	(0.00233)	(0.00173)
Treated	—	—	—	—
Ret		0.0282***		0.0426***
		(0.000515)		(0.000583)
Lr		−3.30e-05*		−0.000471***
		(1.79e-05)		(0.000104)
Np		0.000158***		0.000250***
		(1.07e-05)		(1.33e-05)
Age		6.06e-09		4.26e-09
		(1.29e-08)		(1.16e-08)
Lev		−0.0570***		−0.0573***
		(0.00257)		(0.00244)
Tato		0.0247***		0.0233***
		(0.00119)		(0.00108)
Profit		2.43e-05***		2.27e-05***
		(5.57e-06)		(7.22e-06)
Revenue		−2.58e-05		0.000218*
		(4.94e-05)		(0.000127)
State		0.000658		0.000535
		(0.000541)		(0.000492)
Tq		0.00651***		0.00791***
		(0.000341)		(0.000367)
Constant	0.0434***	0.0274***	0.0426***	0.0229***
	(0.00169)	(0.00446)	(0.00170)	(0.00408)
Enterprise	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Number of enterprises	1,018	1,018	1,018	1,018
R-squared	0.001	0.333	0.001	0.452

Note: standard errors in parentheses, $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

TABLE 6 Regression results after replacing control variables.

Variable name	Full sample		PSM sample	
	No control variables	Control variables	No control variables	Control variables
Time × Treated	0.00385	0.00266*	0.00605	0.00253*
	(0.00336)	(0.00161)	(0.00654)	(0.00285)
Time	0.00168	−0.000260	−0.00205	9.46e-05
	(0.00268)	(0.00129)	(0.00673)	(0.00290)
Treated	—	—	—	—
Ret		0.0133*		0.00871***
		(0.00795)		(0.00101)
Roe		0.186***		0.308***
		(0.0341)		(0.00672)
Size		−0***		−0***
		(0)		(0)
Age		8.90e-09		9.05e-09
		(7.70e-09)		(8.55e-09)
Lev		−0.0470***		−0.0512***
		(0.00406)		(0.00408)
Tato		0.00796***		0.00589***
		(0.00281)		(0.00142)
Profit		0.0000139		−2.39e-05
		(0.0000115)		(2.38e-05)
Revenue		0.0000208		−0.000172
		(0.0000202)		(0.000275)
State		0.000565		0.000819
		(0.000415)		(0.000792)
Tq		0.00479***		0.00666***
		(0.000652)		(0.000704)
Constant	0.0332***	0.0256***	0.0481***	0.0175***
	(0.00194)	(0.00405)	(0.00510)	(0.00468)
Enterprise	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Number of enterprises	1,022	1,017	771	771
R-squared	0.001	0.587	0.008	0.818

Note: standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

show that the coefficient of Time × Treated is significantly positive, indicating that green credit policy makes construction energy-saving enterprises perform better, supporting the view of H1. Models (2) and (4) are the second step, which investigates the effect of Time × Treated on the mediating variables (Shortdebt and Longdebt). The coefficient of the Time × Treated is significantly positive at the 1% level when the mediating variable is Shortdebt, indicating that green credit policy has a positive effect on the short-term debt of construction energy-saving enterprises. Whereas when the mediating variable is Longdebt, the coefficient of Time × Treated is positive but insignificant. There is not enough evidence that the introduction of green credit policy has a significant impact on the long-term debt of construction energy-saving enterprises. Models (3) and (5) are the third step, which examines the effect of *ROTA* on the mediating variables (Shortdebt and Longdebt). The results show that the coefficient is significantly positive when the mediating variable is Shortdebt, indicating that the financial performance of construction energy-saving enterprises is positively correlated with short-term debt. Short-term debt is a vital factor affecting the financial performance of construction energy-saving enterprises. While the

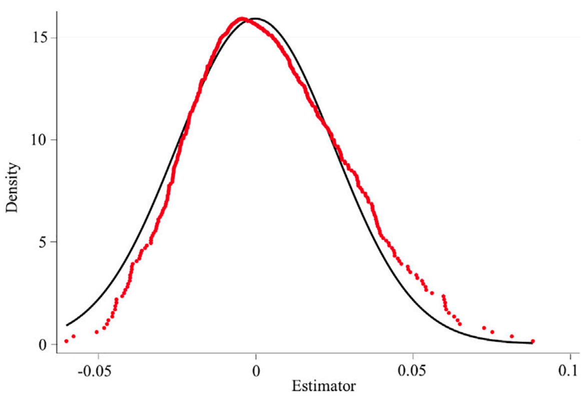

FIGURE 2
Placebo effect test.

coefficient is positive but insignificant when the mediating variable is Longdebt, it fails to draw the same conclusions as short-term debts. In addition, this study provided three significant tests during the mediation command test (Sobel, Doodman1, and Goodman2 tests), all of which were found to be significant. Taken together, short-term debt has a mediation effect between the introduction of green credit policy and the financial performance of construction energy-saving enterprises. We identified a mechanism for the impact of green credit policy on the construction energy-saving enterprises, which is "green credit policy-short-term debt-financial performance of construction energy-saving enterprises." Combined with the above analysis, H2a and H3a are confirmed without supporting H2b and H3b.

4.4 Heterogeneity analysis

To further investigate whether the controlling shareholders affect the effectiveness of introducing green credit policy, this study divides the full sample and the PSM sample into SOEs and non-SOEs and then analyzes them in the subsample. Table 8 shows that the coefficients are larger (and significant) for non-SOEs in both the full sample and the PSM sample, indicating the impact of green credit policy on the financial performance of non-SOEs in construction energy-saving enterprises is more pronounced. But this is the opposite of H3. Though many studies contradict our findings (Hu et al., 2021; Chai et al., 2022; Chen Z et al., 2022), it seems to imply that the green credit policy may be beneficial to non-SOEs for construction

TABLE 7 Mediation effect test based on short-term debt and long-term debt.

Variable name	Short-term debt			Long-term debt		
	ROTA	Shortdebt	ROTA	ROTA	Longdebt	ROTA
	Model (1)	Model (2)	Model (3)	Model (1)	Model (4)	Model (5)
Constant	0.0400***	8.16e + 08***	0.0399***	0.0400***	1.04e + 09***	0.0399***
	(0.00134)	(1.46e + 08)	(0.00135)	(0.00134)	(2.59e + 08)	(0.0013)
Time × Treated	0.00356*	1.36e + 09***	0.00336*	0.00356*	2.40e + 08	0.00336
	(0.00207)	(2.25e + 08)	(0.00207)	(0.00207)	(3.99e + 08)	(0.00207)
Shortdebt			1.46e-13*			
			(8.33e-14)			
Longdebt						2.87e-14
						(4.71e-14)
Control variable	YES	YES	YES	YES	YES	YES
R-squared	0.3523	0.0464	0.3525	0.3523	0.0328	0.3523
F-value	601.05***	53.80***	551.31***	601.05***	37.52***	550.96***
Observations	12,166	12,166	12,166	12,166	12,166	12,166
Sobel test	0.0021*(z = 1.678)	6.899e-06 (z = 0.429)				
Goodman 1	0.0021*(z = 1.657)	6.899e-06 (z = 0.279)				
Goodman 2	0.0021*(z = 1.699)	6.899e-06 (z =)				
Indirect effect	0.0002*(z = 1.678)	6.9e-06 (z = 0.428)				
Direct effect	0.0034 (z = 1.619)	0.0035*(z = 1.713)				
Total effect	0.0035*(z = 1.717)	0.0036*(z = 1.717)				

Note: standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 8 A test of the impact of green credit policy on the financial performance of construction energy-saving enterprises under the difference of controlling shareholders.

Variable name	Full sample		PSM sample	
	SOEs	Non-SOEs	SOEs	Non-SOEs
Time × Treated	0.00334	0.0104*	0.00576	0.0246***
	(0.00236)	(0.00597)	(0.00510)	(0.00932)
Time	−0.000305	−0.00340	0.00431	0.000837
	(0.00208)	(0.00325)	(0.00399)	(0.00622)
Treated	—	—	—	—
Ret	0.0152	0.0709***	0.0266***	0.0595***
	(0.00972)	(0.00667)	(0.00754)	(0.00982)
Lr	−7.70e-05***	−9.97e-05*	−0.000784	0.000398
	(1.35e-05)	(5.55e-05)	(0.000479)	(0.00157)
Np	0.000220***	8.18e-05	0.000274	−7.66e-06
	(7.74e-05)	(7.11e-05)	(0.000182)	(3.07e-05)
Age	−2.30e-09	2.16e-08***	−3.49e-08***	2.58e-08***
	(1.77e-08)	(4.54e-09)	(6.95e-09)	(7.61e-09)
Lev	−0.0646***	−0.0388***	−0.0629***	−0.0233
	(0.00602)	(0.0104)	(0.0120)	(0.0223)
Tato	0.0104**	0.0244***	0.0240***	−0.00263
	(0.00420)	(0.00524)	(0.00415)	(0.00411)
Profit	9.76e-06	7.53e-05	1.90e-05	0.00104**
	(7.85e-06)	(7.32e-05)	(5.23e-05)	(0.000451)
Revenue	−0.000136	8.17e-05	-0.000787*	−0.00695***
	(0.000143)	(9.08e-05)	(0.000469)	(0.00263)
Tq	0.00778***	0.00500***	0.0120***	0.00912**
	(0.000829)	(0.000888)	(0.00225)	(0.00367)
State	—	—	—	—
Constant	0.0422***	0.00972	0.0314***	0.00474
	(0.00739)	(0.00628)	(0.00740)	(0.0160)
Enterprise	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Number of enterprises	738	432	561	234
R-squared	0.268	0.540	0.474	0.668

Note: standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

sectors with different controlling shareholders, which needs further investigation.

5 Discussion and implications

The results of numerous green credit policy studies show that these policies affect enterprises' financial performance (Fried et al., 2002; Loderer and Waelchli, 2011; Brandstädter et al., 2012; Cheng and Lu, 2017; Zheng et al., 2021). However, most of the research on green credit has focused on enterprises that are heavily polluted, and less on construction energy-saving enterprises. Therefore, this study examines the impact of green credit policy on the financial performance of construction energy-saving enterprises using A-share enterprises (divided into construction energy-saving enterprises and non-construction energy-saving enterprises) from 2004 to 2020. We used PSM to match the observations and built a DID model to evaluate the effect of introducing green credit policy. Additionally, we analyzed the mechanism of the impact of green credit policy on the financial performance of construction energy-saving enterprises by a mediation effect model. Further, we categorized the sample according to the controlling shareholders (SOEs and non-SOEs) to explore the impact of green credit policy on each subsample.

5.1 Theoretical implications

This study highlights several intriguing theoretical implications.

Firstly, green credit policy has contributed significantly to the financial performance of construction energy-saving enterprises. Some previous studies find that green credit significantly improved the financial performance of eco-friendly enterprises (Yao et al., 2021; Lai et al., 2022), which is consistent with our results. We extend the research to the construction industry. With the introduction of green credit policy, financial institutions are required to comprehensively consider the environmental behavior of enterprises in their credit decisioning, according to the requirements of national policies. Meanwhile, environmental risk is the main basis for measuring credit risk. As a result, financial institutions prefer less risky enterprises to finance. Indeed, construction energy-saving enterprises are environmentally friendly and virtually immune to environmental risks. From a profitability and security perspective, the cost of credit financing for construction energy-saving enterprises is significantly lower than for non-construction energy-saving enterprises, thereby improving the financial performance of construction energy-saving enterprises. More importantly, financial institutions cannot suffer reputational damage by establishing credit relationships with enterprises involved in environmental incidents.

Secondly, the financial performance of construction energy-saving enterprises is positively related to short-term debt, and short-term debt is a mediating variable between green credit policy and the financial performance of construction energy-saving enterprises. This study enriches the green credit research of the construction industry by revealing how debt meditates this green credit policy-financial performance relationship. We identified the mechanism by which green credit policy affects construction energy-saving enterprises, namely "green credit policy-short-term debt-financial performance of construction energy-saving enterprises." One of the core elements of the green credit policy is that for environmentally friendly enterprises and projects, banks will support them in terms of loan interest rates, loan terms, loan support amounts and loan types. Specifically, financial institutions offer loans to heavily polluting enterprises at higher interest rates than energy-saving enterprises, thereby causing heavily polluting enterprises to reduce the scale of production and reduce environmental pollution. Hence, financial institutions will provide support to construction energy-saving enterprises and promote their development.

Thirdly, the impact of green credit policy on the financial performance of non-SOEs (construction energy-saving enterprises) is more significant. Chai et al. (2022) found that SOEs are more affected by green credit policy than non-SOEs. Hu et al. (2021) confirmed that heavily polluting SOEs have greater credit constraints than non-SOEs. Chen L et al. (2022) concluded that green credit policy has a more significant contribution to low carbon technology innovation in SOEs. A unifying view that seems to emerge from all of the above studies is that as SASAC[3]-controlled enterprises, SOEs are subject to greater state regulation and control, ultimately leading to higher output for SOEs than non-SOEs. This view is contrary to the findings of this study, and an in-depth analysis of the data suggests that the reasons for the opposite conclusion are twofold. On the one hand, SOEs are generally thought to forgo maximum profit in the pursuit of social and political objectives. And non-SOEs are more profitable than SOEs (Dewenter and Malatesta, 2001). On the other hand, while the green credit guidelines were introduced in 2012, their application in the construction sector actually started late and developed slowly. Therefore, the impact of the construction sector on SOEs and non-SOEs may not be significantly different.

5.2 Policy implications

Green credit policy helps encourage construction energy-saving enterprises to fulfill their social responsibility to protect the environment. It can greatly facilitate the development of green enterprises in China and aid the country in achieving comprehensive, coordinated, and sustainable economic growth.

Firstly, the government, banks and enterprises need to improve the green credit policy. We find that green credit will benefit environmentally friendly enterprises. The government needs to develop actionable introduction rules based on business operations and establish an incentive mechanism, as well as a regulatory system, that matches the green credit policy. Moreover, it should strictly check the flow of green credit capital and dedicate green loans to specific purposes. Commercial banks need to carry out targeted corporate credit assessment mechanisms. Specifically, this means establishing a credit management system that meets the characteristics of green lenders and dynamically adjusting credit resources according to the

3 State-owned Assets Supervision and Administration Commission of the State Council (SASAC) is for the State Council directly under the ad hoc institutions.

specific conditions of enterprises. Meanwhile, a relevant information management platform can be established to realize information sharing between enterprises and banks to ensure that the introduction of the policy can achieve the expected effect and form a positive social impact. Enterprises should strengthen their awareness of environmental protection, pay attention to internal green governance, and consciously assume social responsibility for ecological protection. They should make full use of the development opportunities brought by the national green credit policy to change production methods, enhance green technology innovation, accelerate the green transformation and upgrade enterprise structures, and promote green and efficient development of enterprises.

Secondly, this study confirms that short-term debt positively affects the financial performance of construction energy-saving enterprises as a mediating variable. Banks can decrease the maturity of some debt relating to "sustainable finance," and governments can provide more supportive policies for the short-term debt of construction energy-saving enterprises. These measures promote enterprises to restructure their capital and reduce the cost of financing to protect against risk.

Thirdly, the government should strengthen the external supervision and discipline of SOEs. The results of heterogeneity analysis indicate that the impact of green credit policy on the financial performance of non-SOEs was more pronounced compared to SOEs. While policy changes can lead to improvements in SOEs performance, the improvements may dissipate over time without added discipline (Yarrow et al., 1986). Non-SOEs tend to take action in light of the maximization of enterprises' value and contribute more to economic growth (Chang et al., 2015). Policies that explicitly mix economic and political interests and incentives to enterprises should be encouraged.

6 Conclusion and future directions

Based on secondary data of A-share enterprises (divided into construction energy-saving enterprises and non-construction energy-saving enterprises) from 2004 to 2020, we use PSM to match the data and build a DID model to evaluate the effect of introducing green credit policy. First, this study proposes a set of hypotheses combined with existing green credit and financial performance literature. Second, this study defined the research variables and models. Third, this study conducted descriptive statistics, PSM test, balance test, DID test, and robustness tests to analyze the empirical results, and verified the hypotheses.

This study revealed that the introduction of the green credit policy makes the financial performance of construction energy-saving enterprises increase remarkably. Environmentally friendly enterprises benefit from green credit policy. Furthermore, short-term debt has a positive mediation effect between the introduction of green credit policy and the financial performance of construction energy-saving enterprises. In the context of green credit policy, appropriately higher levels of short-term debt can contribute to enterprises' financial performance. This study enriches the empirical research of green credit-financial performance relationship with the mediating effect of enterprises' debt in the construction sector. Finally, the heterogeneity analysis concludes that the impact of green credit policy on the financial performance of non-SOEs in construction energy-saving enterprises is more pronounced. This study explores the introduction effects of the green credit policy on the financial performance of Chinese construction energy-saving enterprises. The findings provide practical guidance for the government, banks and enterprises to promote the sustainable development of the construction sector.

Although this study has come to several conclusions, it also suggests further investigation. First, China launched the green credit policy in 2012, their application in the construction sector started late and developed slowly. Using the PSM-DID method to empirically test the impact mechanism of the green credit policy may require a longer period. There are many problems in the introduction of a policy during the early stages of implementation, so the effectiveness of the policy will become more accurate over time. We can do more tracking studies in the future. Second, in future studies, we can explore a more nuanced influencing mechanism of green credit policy on the financial performance of construction energy-saving enterprises. For example, the conditions of enterprises' environmental protection (He et al., 2019b), enterprise characteristics (Mcintyre et al., 2007), regional economic development (Lai et al., 2022), and capital (Hu et al., 2020), which are hot topics of discussion in corporate governance studies. Future studies could investigate their role in the relationship between green credit policy and financial performance.

Data availability statement

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

Author contributions

LX and LY contributed to conception and design of the study. LX organized the database and performed the statistical analysis. LX and LY wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1004247/full#supplementary-material

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The Impact of Government Behaviors on the Transition Towards Carbon Neutrality in the Construction Industry: A Perspective of the Whole Life Cycle of Buildings

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The carbon-intensive economy has dramatically caused global climate changes and profoundly impacted humankind. As one of the largest energy consumers, carbon emissions in the construction industry (CECI) play a crucial role in achieving the carbon neutrality goal. Government behaviors could significantly affect CECI. However, few studies have comprehensively reviewed existing literature regarding the effect of government instruments on triggering carbon reduction. A total of 1,082 papers about CECI from 51 countries/regions were retrieved in this study, while 296 relevant articles on the government behaviors in CECI were collected to conduct further analysis. Based on the bibliometric analysis with CiteSpace, the co-occurrence networks of countries/regions, institutions, keywords and cluster analysis are applied to illustrate the characteristics of previous studies. Furthermore, a research framework has been formulated to review the impact of government behaviors on CECI during the life cycle of buildings. The result indicated that government behaviors could affect CECI through three stages, i.e., material production, construction and operation, which is considered the transmission path of government behaviors towards CECI. Moreover, the findings revealed that government behaviors present the most significant impact on CECI in the following sectors: 1) the green supply chain management and waste recycling in the material production stage; 2) the green building decisions and the adoption of off-site construction in the construction stage; 3) energy conservation behaviors and green retrofit decisions in the operation stage. Finally, this study discusses prior study gaps and provides potential directions for future research.

Keywords: carbon neutrality, carbon emissions, construction industry, government behaviors, whole life cycle

1 INTRODUCTION

Since the early 20th century, carbon-intensive economy has contributed to a 1°C rise in the global average temperature (Rueda et al., 2021), and climate changes caused by carbon emissions have profoundly affected humankind (Yang et al., 2022). As the sector of high energy consumption, the construction industry has contributed quantities of carbon emissions to the world (Lee et al., 2020; Su et al., 2022). Global CO_2 emissions from the buildings sector totaled about 1 billion tons in 2019, accounting for 28% of the world's energy-related carbon emissions, rising to 38% when the construction industry component [the part of the industry used to make building materials such as steel, cement and glass (estimated) is added] is included (IEA, 2021). The Intergovernmental Panel on Climate Change (IPCC) report complied by 278 scientists from 65 countries highlights the magnitude of a comprehensive transformation of the construction industry's emission reduction path (IPCC, 2022). Against the United Nations Framework Convention on Climate Change (UNFCCC), governments worldwide have set respective goals to mitigate carbon emissions. In 2015, the Paris Agreement was adopted by 196 Parties at COP 21 in Paris, a legally binding international treaty on climate change (Paris Agreement, 2015), in which 90 countries have included actions to address building-related emissions or improve energy efficiency in the Paris Agreement. Based on the principle of common but differentiated responsibilities, Chinese government pledged at Paris Climate Conference in 2015 that China would stop increasing its total CO_2 emissions no later than 2030 (Chen J. et al., 2021). Until 2020, 136 countries mentioned emissions reductions in their nationally determined contributions.

An innovative transition to low carbon development in the construction sector is required, which has become a hot topic in the academic and industry community. Developing countries account for 58% of global carbon emissions (Zheng, 2021). Since the last financial crisis, China, as the largest country in the emerging market, has become the world's largest carbon emitter (Wu et al., 2019). Chen et al. (2017a) proved that the CECI consisted of as large as 22.5%–33.4% of the total emissions in China during 1995–2011. To fulfill global responsibility for the green and low-carbon mission, China proposes to achieve carbon peak by 2030 and carbon neutrality by 2060 at the General Debate of the 75th Session of The United Nations General Assembly (Xi, 2020), for which China has set compulsory carbon reduction targets for the construction industry in each province (Wen and Wang, 2020). On account of this, mitigating carbon emissions in the construction industry (CECI) is crucial to achieving the carbon neutrality goal.

The government has played an irreplaceable role in construction carbon reduction with reduced environmental impact (Sunikka, 2006; Ismailos and Touchie, 2017). Government behaviors include law, executive order, reward and compensation (Saka et al., 2021). For industries, the adverse effects of their carbon emissions can be seen as externalities of their economic activities, and there are various ways to internalize the externality of economic activities (Li and Colombier, 2011). In response to this problem in the construction industry, governments typically face a two-step strategy: first, setting environmental targets (e.g., carbon emission mitigation); second, selecting policy tools based on various targets (Stavins, 1996). Policies are a strategic tool for the government to achieve the established goals (Liu et al., 2020), while government policies and market mechanisms can significantly impact technological innovation in construction projects (Wu et al., 2017).

At present, the government has implemented various strategies to reduce CECI. For example, the government has adopted six measures, including regulation-based and direction-based policies, to stimulate green retrofit (Tan et al., 2018). Furthermore, five measures that involve incentives, standards, regulations, guidance and initiatives are implemented to promote off-site construction (Luo et al., 2021). Moreover, some regulations, directives and initiatives have been adopted to intensify the recycling of construction and demolition waste (Kylili and Fokaides, 2017). Government behaviors will clearly affect corporate carbon emissions, and policymakers can influence corporate carbon emissions by adopting environmental regulations and economic incentives (Mahmoudi and Rasti-Barzoki, 2018). Meanwhile, government environmental regulations are essential to eco-innovation in the construction sector (Ortiz et al., 2009; Balasubramanian and Shukla, 2017).

Prior studies have investigated the impact of a single government behavior (such as carbon taxes) on carbon emissions, or focused on the impact of different policies on carbon emissions in a single sector of the construction industry (such as off-site construction). However, extant studies rarely reveal holistic research on the impact of government behaviors on carbon emissions from the perspective of the entire life cycle of buildings. It is argued that more attention should be paid to the indirect carbon emissions of the construction industry (Chen et al., 2017b), which is the most significant contributor. This paper proposes a framework to disclose the impact of government behaviors on the whole life cycle of CECI and reviews the impact of government behaviors on each stage.

This paper is organized as follows: The bibliometric analysis with CiteSpace is presented in **Section 2**. Government behaviors and corresponding transmission paths toward CECI are presented in **Section 3**. **Section 4** investigates the impact of government behaviors in the material production stage. The impact of government behaviors in the construction stage is discussed in **Section 5**, and **Section 6** analyzes the impact of government behaviors in the building operation stage. Finally, concluding remarks, limitations and directions for future research are provided in **Section 7**.

2 BIBLIOMETRIC ANALYSIS

2.1 Methodology and Data Collection

Scientometric analysis is a technology that demonstrates the scientific development process and structure relationship based on the knowledge domain (Trofimenko, 1987). Many software have been developed to conduct a scientometric analysis, such as BibExcel, Ucinet, SCIMAT, VOSviewer and CiteSpace (Shi et al., 2019). Among these, CiteSpace incorporates co-occurrence analysis, evolutionary trend detection and visualization functions to provide a mature approach for bibliometric analysis (Chen, 2006, 2017), which has been widely utilized in

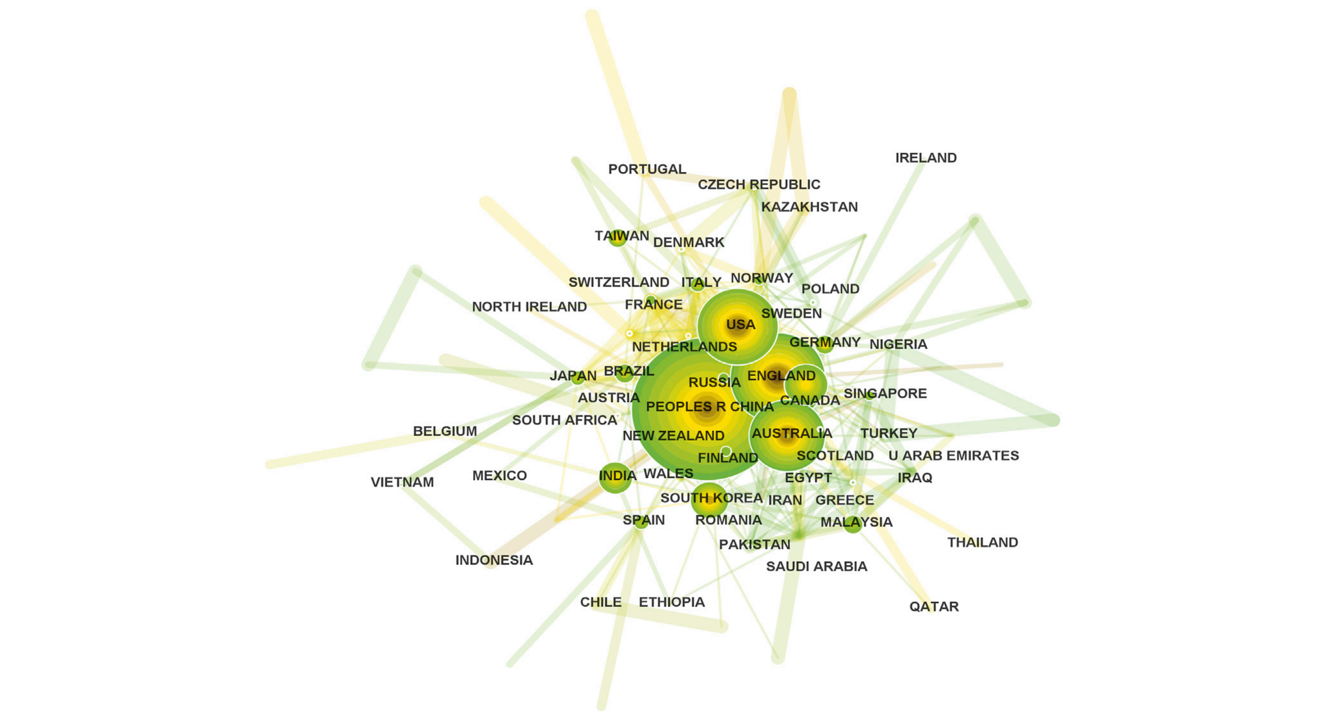

FIGURE 1 | Co-countries/regions network: CECI.

various research fields such as sustainable development (Si et al., 2019; Koondhar et al., 2021; Huang et al., 2022). However, this tool is still less used in the CECI field.

Betweenness centrality and burst strength are two critical indicators in CiteSpace. Betweenness centrality is the ratio of the shortest paths between two nodes to the sum of all shortest paths (Freeman, 1977). Generally speaking, the occurrence of a high betweenness centrality is likely to reveal a transformative discovery (Chen et al., 2009). Citation bursts present keywords repeatedly cited within a specific period (Yu et al., 2017). Burst strength could indicate a sudden change in a citation over a period of time, during which the nodes of high burst strength might be the turning points or milestones in the development of literature themes. This paper used the retrieved result through the core collection database of *Web of Science* (WoS) to conduct a bibliometric analysis.

2.2 Results and Discussion: CECI

This paper conducted two-step bibliometric analyses using different constraints. One step analyzes the existing research on CECI, and the current research on government and CECI is analyzed in another analysis. For the first analysis, the content of string retrieve was set as "TS=("construction industry" AND "carbon emission")". The literature type was set to "journal article" written in English and the database was set to "Web of Science Core Collection" to ensure the quality of our data source. The time span of articles was set as "from 2010-01-01 to 2022-03-05". A total of 1,082 articles were presented according to the above retrieval criteria. The collaboration network of countries/regions captures the contribution network of countries/regions to the body of knowledge of CEIC. **Figure 1** shows that China has the most significant number of publications in all 51 countries, followed by the United Kingdom, the US and Australia, and the topic of carbon emission in the construction sector has been debated among researchers worldwide.

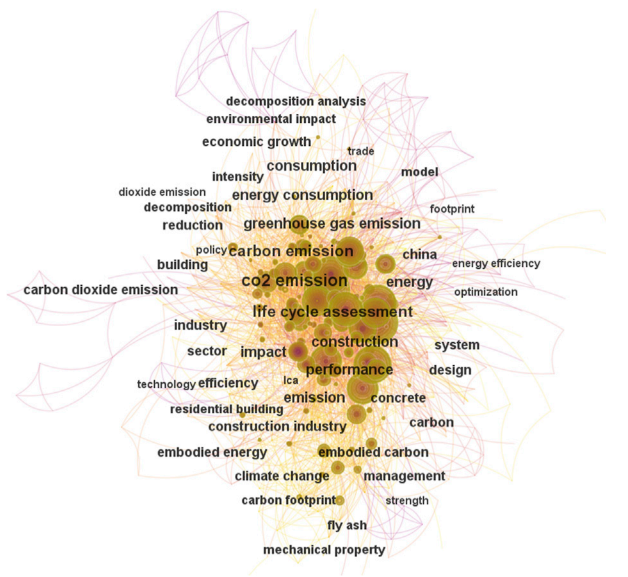

FIGURE 2 | Keywords co-occurrence network: CECI.

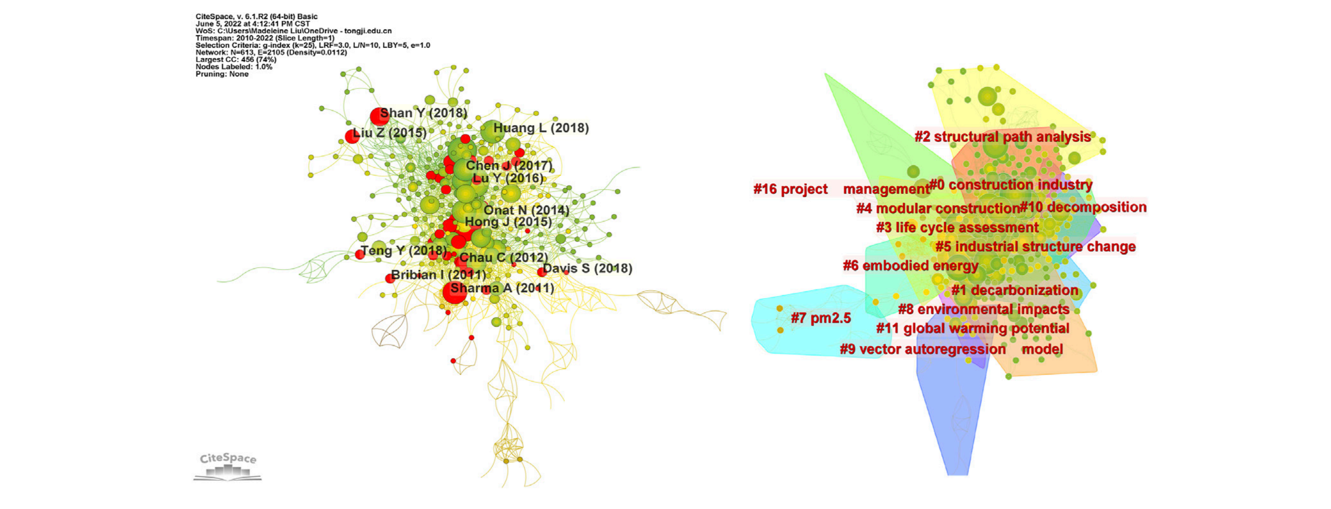

FIGURE 3 | Co-citation network and topic clustering of CECI domains: 2010–2022.

Keywords co-occurrence analysis can demonstrate the keywords that appear most frequently in existing studies and their links, which could help identify the primary topics in the research topic of CECI. The co-occurrence network of keywords is presented in **Figure 2**, which total includes 464 keyword nodes and 2,930 links in prior studies of the CECI field, and the size of each node shows the frequency of keywords appearing. The top five keywords are: CO_2 emission (frequency = 224), carbon emission (frequency = 174), life cycle assessment (frequency = 164), energy (frequency = 119) and construction (frequency = 118).

Figure 3 left-hand presents a co-citation network consisting of 613 nodes and 2,105 links, and the red nodes denote the citation burst, and the color change from brown, yellow to green reflects the time span from past to present (2010–2022). The right side of **Figure 3** demonstrates the cluster analysis of keywords using the Log-Likelihood Ratio (LLR), and thirteen highlighted research clusters were identified. Here, the modularity Q = 0.772 (>0.5), which shows the overall clustering outcomes are significative, while the weighted mean silhouette = 0.878 (>0.8) means that the cluster members have certain similarity and homogeneity. The cluster analysis is an exploratory data mining technique to analyze and identify vital topics, content and interrelationships (Wilks, 2019). The CiteSpace provides access to extract the noun phrases from titles, keywords or abstracts of publications and use them as tags for different groups (Chen, 2006; Si et al., 2019). Among all the clusters, the largest two clusters are #0 (construction industry) and #1 (decarbonization). The former represents the focus of the construction sector on CECI-related research. The cluster "decarbonization" mirrors the decoupling relation between the construction and carbon emissions, and its alternative labels of this cluster include sustainable construction, supply chain, emissions reduction, carbon abatement, carbon mitigation, greenhouse gases, carbon neutrality and so on. For example, the study by Karlsson et al. (2020) indicated that it is technically possible to halve road construction CO_2 emissions with the best available technologies and practices to abate more than three-quarters of the emissions by 2030 and achieve close to net zero emissions by 2045.

The premise of CECI reduction is to clarify the carbon emission source and impact path, which is related to the whole industrial green transition and development. To address this, the research community has carried out a considerable amount of studies to evaluate energy consumption and carbon emissions of the construction sector by different approaches. Furtherly, it has investigated the low-carbon transition of the construction industry, including the cluster #2 (structural path analysis), #3 (life cycle assessment), #4 (modular construction), #5 (industrial structure change), #6 (embodied energy) and #10 (decomposition). For instance, applying the multi-regional structural path and sensitivity analysis model, Chen J. et al. (2022) assessed the structural paths and sensitivity of construction CO_2 emissions in China, India, Japan, Russia, and the United States in 2015. Cluster # 8 (environmental impact) concentrate on 3R (i.e., reduce, reuse and recycling), and keywords labels embody resource recovery, circular economy and waste treatment. For the cluster, Bao and Lu (2021) developed a decision-support framework to plan on-site and

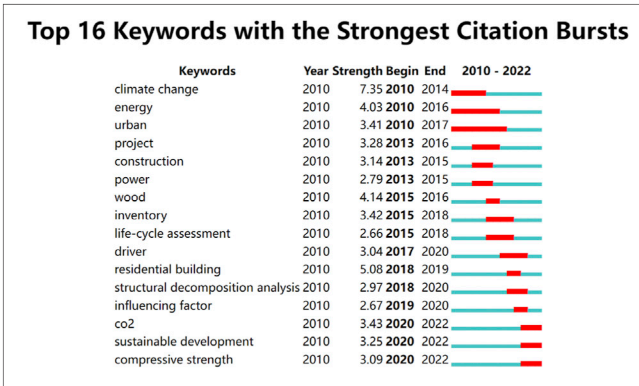

FIGURE 4 | Keywords with the most robust citation bursts: CECI.

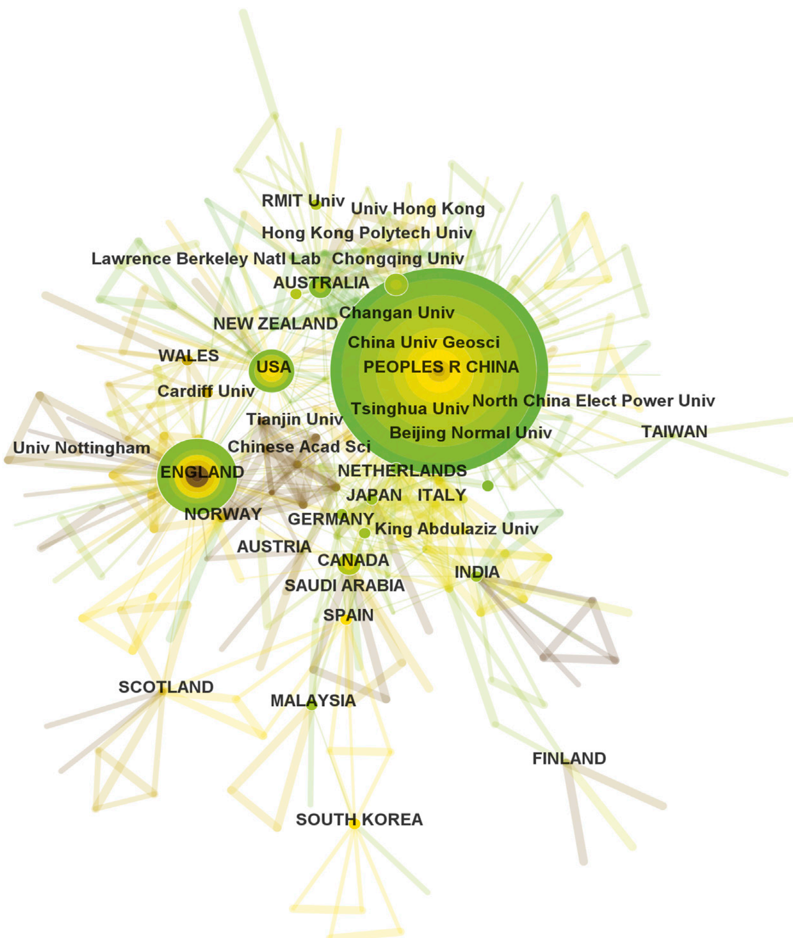

FIGURE 5 | Co-countries/regions and institutions network: CECI and government.

off-site construction waste recycling in the case study of Shenzhen, China.

The keywords bursts in the field of CECI are given in **Figure 4**. Climate change is at the top of the list, with the most robust citation burst of 7.35 from 2010 to 2014. During the 2018–2019 period, the research emphasis on carbon emissions of residential buildings shows an explosive growth (Kneifel et al., 2018; Li et al., 2019). Hotspots in recent years include sustainable development and compressive strength, indicating the construction industry's sustainable transition that incorporates the advancement of techniques and green supply chain management (Ghani et al., 2017; Zhang X. et al., 2022).

2.3 Results and Discussion: CECI and Government

For the second analysis, our keywords for searching included "construction industry" AND "carbon emission" AND "government", and other restrictions are the same as the first time. A total of 296 articles were retrieved, which was greatly reduced compared with the first analysis.

Figure 5 shows the contribution network of countries/regions and institutions to the body of knowledge in the CECI and government perspective. China, the United Kingdom and the United States are still the countries with the largest number of publications in the CECI and government fields, which indicates that research communities from these countries concentrate on the significant roles of government behaviors in carbon reduction action. Active academic communities in Asian-Pacific, European and United States have contributed significantly to the research field on government behaviors of CECI.

Figure 6 shows that in the research field of CECI and Government, impact replaces energy as the top five keywords, and some new perspectives are absorbed, such as innovation and life cycle assessment. Furthermore, there are only three citation bursts in the fields of CECI and government, including management, residential building and design. Though these are not new topics, more microscopic and specific strategy has been discussed in the governmental behavior in this field.

Overall, previous studies have paid attention to governmental behavior in the CECI. Some researchers have tried to reveal the process in specific conditions from various perspectives, such as policy incentives in residential buildings (Ismailos and Touchie,

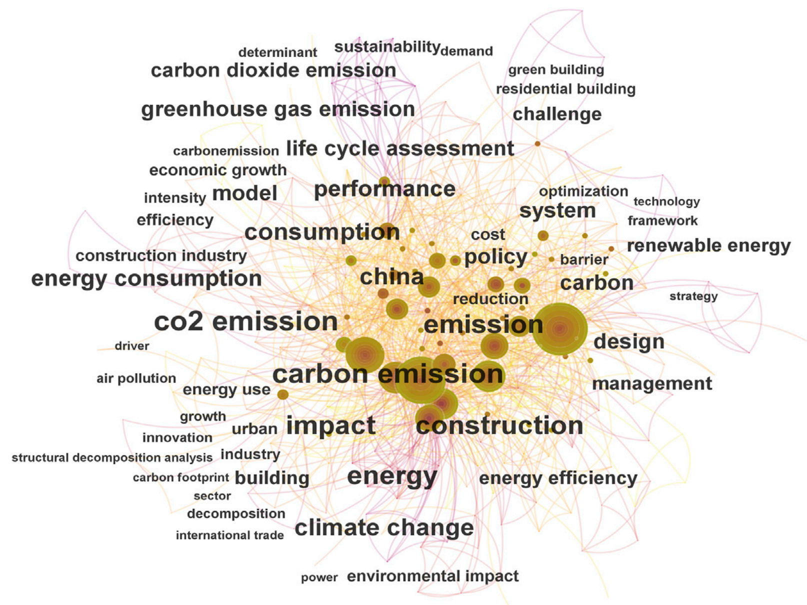

FIGURE 6 | Keywords co-occurrence network: CECI and government.

2017; Huo et al., 2021), carbon reduction in green buildings (Berry et al., 2014; Hope and Booth, 2014), and government role in construction waste recycling (Bao et al., 2019; Bao and Lu, 2020). However, few studies have investigated the government's role in CECI from the life cycle perspective. Thus, a more systematic review of government behaviors in CECI could effectively disclose the influencing path and identify internal barriers, which promote the effectiveness and efficiency of government instruments in carbon reduction in the construction sector.

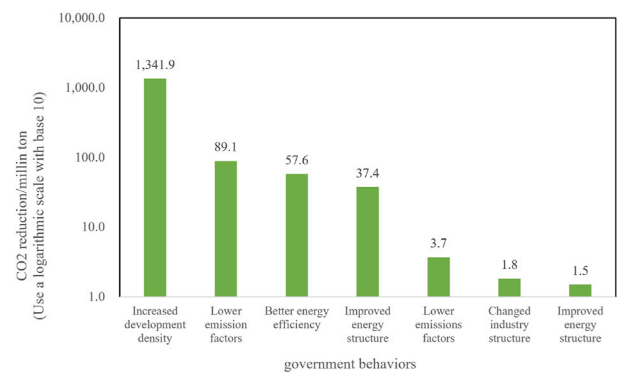

FIGURE 7 | Impact of different government behaviors on CO_2 reduction [The picture is drawn by the authors with data source from Wu et al. (2019)].

3 GOVERNMENT BEHAVIORS AND TRANSMISSION PATH

3.1 Government Behaviors

Government can encourage and restrict the construction industry by law, executive order, reward and financial allowance (Saleh and Al-Swidi, 2019). Law and executive orders are compulsory, whereas rewards and allowances are encouraging and voluntary for stakeholders in the construction sector (Saka et al., 2021). Li and Colombier (2011) have divided the governmental tools to regulate energy consumption into two categories, incentives-based instruments and regulatory measures. The former is considered the most cost-effective, while the latter can also contribute to mitigating carbon emissions. Xie et al. (2022) have generalized government intervention into two categories, government support and environmental regulations, and studied their impact on the construction industry separately.

Policy instruments can also be divided into three policy types: supply-side, demand-side, and environmental-side (Wang and Zou, 2018; Xue et al., 2021). In the field of carbon emissions, supply-side policies frequently used by the government include establishing uniform supply standards, increasing training for workers and investing in establishing information platforms. The demand-side policy is a policy tool used by the government to help accelerate innovation by stimulating the demand for innovation. The commonly used demand-side policies include trade supervision and government procurement (Creutzig et al., 2018). Environmental-side policies are always market-based instruments, which could guide the behaviors of stakeholders through market signals released by decision-makers (Wolde-Rufael and Weldemeskel, 2020). Furthermore, in Finland and the United Kingdom, governmental policies can be divided into three categories: economic, regulatory, and soft (Kern et al., 2017). Liu et al. (2020) summarized six types of policies: control, technology, economic incentives, certification, information, and organization and professional.

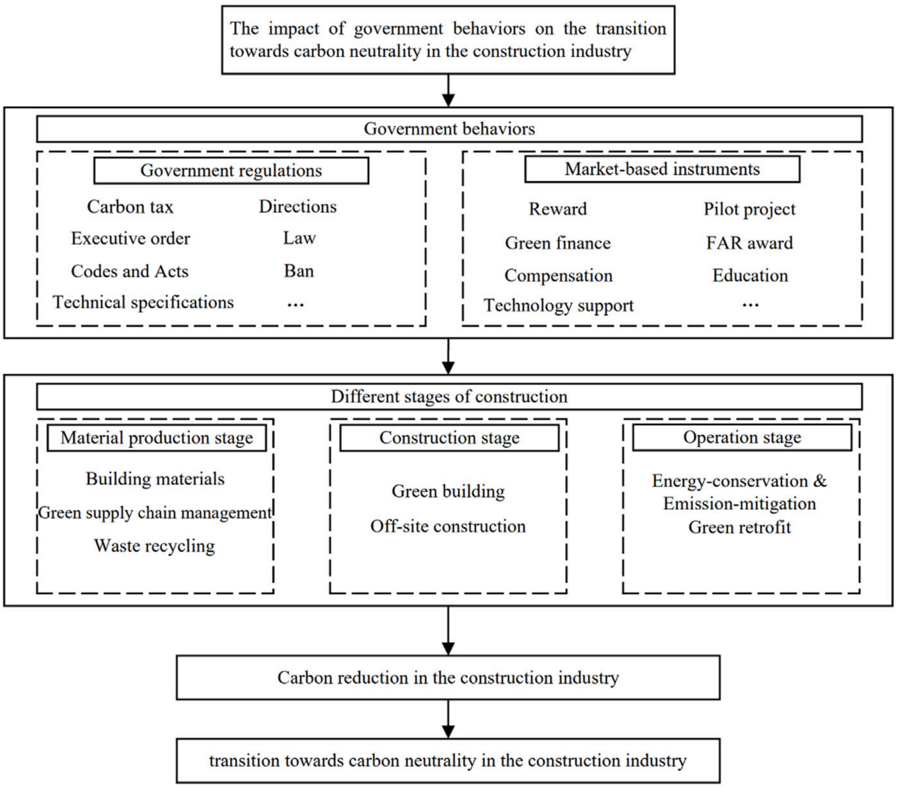

FIGURE 8 | The transmission path of government behaviors towards CECI.

Simultaneously, the effect of different government actions on reducing CECI is different. Environmental-side policies are most frequently adopted by the Chinese government, and "regulation control" and "goal-planning" instruments are the ones most widely applied (Liao, 2016). Ozorhon (2013) probed the response of construction clients to low-carbon building regulations and governmental policies. Wu et al. (2019) investigated the carbon reduction effect of government behaviors and quantified it (**Figure 7**).

This study categorizes government behaviors as government regulations and market-based instruments according to whether they are mandatory or optional. Stakeholders in the construction industry must accept the former but can decide whether to adopt the latter in line with specific market conditions and development strategies.

3.2 Transmission Path

Carbon emissions in the construction industry can be divided into operational and embodied carbon emissions, in which embodied carbon emissions include direct and indirect emissions (Giesekam et al., 2014). Li et al. (2020) summarized it as

$$\boldsymbol{C} = \boldsymbol{C_D} + \boldsymbol{C_I} + \boldsymbol{C_O}$$

where C represents the total carbon emissions of the construction industry, and C_D, C_I and C_O denote the direct carbon emissions, indirect carbon emissions and carbon emissions generated during the building operation, respectively.

Researchers classified the construction sector into various stages to adapt their study focus. Hong et al. (2014) divided construction into three stages: material manufacturing, transportation, and on-site construction, to examine the carbon emissions of the Korean construction industry. Li et al. (2017) have calculated the embodied carbon in the life cycle of a residential building, which is divided into five stages, including materials production, transportation, construction, maintenance, and demolition and disposal. Lu et al. (2018) decomposed the carbon emissions of the construction industry into three stages of material production, construction and operation, and found that the material production stage emits the most greenhouse gases based on empirical research in China. Ruiz and Guevara (2021) disclosed the impact of policies on different stages (design, construction, and operation) of the life cycle of social housing units.

Based on the summary of previous studies, this study proposes that government behaviors can affect CECI *via* exerting impacts on three stages during the life cycle of buildings, including material production, construction and operation, indicating that different stages in the life cycle of buildings are the transmission path towards CECI for government behaviors. Given this context, this study establishes a research framework to analyze the impact of government behaviors on CECI and reviews the impact of each government behavior (**Figure 8**). As

TABLE 1 | Representative literature about government behaviors in the material production stage.

Sector	Policy classification	References	Tools studied
Building materials	Government regulations	Nabernegg et al. (2019)	Taxes
		Tangtinthai et al. (2019)	
		Kylili and Fokaides (2017)	Legislation and administrative orders
		Wu et al. (2019)	
	Market-based instruments	Chen et al. (2022b)	Technical standards
		Akan et al. (2017)	
Green supply chain management	Government regulations	Xie et al. (2022)	Environmental regulations
		Zakeri et al. (2015)	Carbon tax
		Halat et al. (2021)	
		Luo et al. (2022)	
	Market-based instruments	Xie et al. (2022)	Government support
		Zakeri et al. (2015)	Carbon price and carbon trading
Waste recycling	Government regulations	Yan et al. (2014)	Legislative and regulatory change
		Kylili and Fokaides (2017)	
		Karlsson et al. (2020)	
		Doust et al. (2021)	
		Kylili and Fokaides (2017)	Taxes
		Di Maria et al. (2018)	
		Hoang et al. (2021)	
	Market-based instruments	Kylili and Fokaides (2017)	Sustainable systems
		Di Maria et al. (2018)	
		Bao et al. (2021)	
		Yu et al. (2022)	
		Bao et al. (2019)	Green government procurement
		Hoang et al. (2021)	
		Nussholz et al. (2019)	Guidance and support
		Bao and Lu (2021)	
		Wang et al. (2021a)	

the framework shows, government behaviors on CECI embodied in the policy toolkit, industry standards and corresponding behavioral supervision, which could affect construction carbon emissions directly (construction stage) and indirectly (material production and operation stages) through the flow of the life cycle of buildings.

Sections 4, **5** and **6** reviewed prior studies and discussed the governmental impact mechanism of carbon reduction to illustrate the role of government instruments in different stages.

4 MATERIAL PRODUCTION STAGE

In the material production stage, government behaviors can influence CECI through building material production, material supply chain and waste recycling. **Table 1** shows representative research on this topic.

4.1 Building Materials

The production and transportation of building materials generate a large amount of carbon emissions. A process-based life cycle assessment incorporating an extended system boundary indicated that 94.36% of all indirect emissions is caused by the production of building materials, whose transportation accounts for a share of 3.64% (Hong et al., 2015). Wu et al. (2019) used Logarithmic Mean Divisia Index to analyze CECI from the perspective of a life cycle, and found that CECI mainly comes from the manufacturing of building materials and the operation of buildings, which account for 58 and 40%, respectively. In the extraction phase of raw materials, CECI also constitutes the most significant proportion (Gan et al., 2018). In 2017, the construction industry consumed 25% of annual steel production and 75% of cement production in China (Shi et al., 2017).

Government behaviors can indirectly affect CECI by affecting the production and transportation of building materials. By combining a Computable General Equilibrium and a Multi-Regional Input-Output model, Nabernegg et al. (2019) researched Austria's carbon emission policy in the construction sector and found that the government's carbon tax on additional carbon emitted in the building materials production stage performs effectively in reducing carbon emissions. Kylili and Fokaides (2017) proposed that the government could adopt legislation to ensure the sustainable development of building materials. Tangtinthai et al. (2019) believed that the Thai government should introduce environmental taxes on the extraction, processing and disposal of building materials to reduce CECI. During China's 12th Five-year Plan (2011–2015), due to the overcapacity of steel and aluminum, China's carbon emissions from construction raw materials soared from 1.32 billion tons to 2.63 billion tons. Therefore, Chinese government adopted laws and administrative orders, such as Guiding Opinions of the State Council on Resolving Serious Production Overcapacity Conflicts, to optimize the excess capacity upstream of the construction industry and reduce CECI (Wu et al., 2019).

Carbon emissions vary in multiple building materials (Ouyang and Lin, 2015), and carbon cut action could be more targeted. Chen M. et al. (2022), Chen et al. (2022c) found that among all building materials, cement, brick, steel, asphalt felt and lime contributed about 93.1% of the total embodied energy and 95.7% of the total embodied carbon. Furtherly, steel and linoleum were not used much in the construction process but were the primary sources of carbon emissions, while sand and gravel were consumed most but contributed less carbon emissions during construction, so they proposed that government should consider this situation when making decisions. Akan et al. (2017) investigated the measurement of the total greenhouse gas emissions for a tunnel construction project by a Turkish firm, which argued that the government and industry associations could affect the supply chain of the construction industry by promulgating relevant regulations on concrete production technology, thereby indirectly affecting the CECI.

4.2 Green Supply Chain Management

Government behaviors can also mediately affect carbon emissions *via* impact on the supply chain of the construction industry, such as the transportation of building materials and stakeholders in the supply chain. However, previous research merely considered the concept of Green Supply Chain Management (GSCM) in construction (Wibowo et al., 2018), and only 1.39% of all GSCM studies focused on the construction industry (Bhatia and Gangwani, 2021).

The government can promote the implementation of GSCM in the construction industry by means of law and executive orders, and the government's incentives and support also contribute to the application of GSCM. Xie et al. (2022) studied the effect of government support and environmental regulations on GSCM in the construction industry. Generally, environmental regulations focus on command-and-control, whereas government support is market-based and can clarify top-level environmental objectives. Their empirical study found that environmental regulations can exert pressure on stakeholders in the construction industry and, therefore, force them to obey the laws, and government support can promote the execution of GSCM; both support and regulations can indirectly contribute to the reduction of carbon emissions by employing GSCM.

As the carbon emissions of the supply chain network account for an increasing proportion of the impact of global climate change (Wang et al., 2019), carbon price and carbon trading are also applied in supply chain management to promote carbon reduction (Zakeri et al., 2015). The government can influence the supply chain through carbon tax, whereas the design of carbon tax policy and the structure of the supply chain will affect the outcomes of the policy. Luo et al. (2022) used four game-theoretic models to evaluate the impact of carbon tax policy on a closed-loop supply chain. They found that carbon tax policies can encourage producers to invest in technical innovation to reduce carbon emissions when adequately designed, but unreasonable carbon tax policies would perform oppositely. It is argued that the government could encourage low-carbon consumption by subsidizing the demand side to reduce carbon emissions. Halat et al. (2021) investigated carbon tax policy in inventory games of multi-echelon supply chains, and found that the government can affect the supply chain through the carbon tax to reduce carbon emissions. However, for supply chains with a relatively high cooperation structure, an excessive carbon tax will reduce the effect of carbon emission reduction, so a high carbon tax is more effective for decentralized supply chains. Meanwhile, it is notable for the public departments to establish a mandatory regulatory platform and incentive market mechanism for firms' environmental information disclosure (Wang et al., 2022).

4.3 Waste Recycling

Large amounts of construction and demolition waste (CDW) are continuously generated along with construction activities (Akhtar and Sarmah, 2018; Hao et al., 2021). As one of the most extensive waste types, CDW includes wood, bricks, glass, plastics, concrete and steel (Yazdanbakhsh, 2018), whereas only 5%–15% of China's annual 1,500 million tons CDW is eventually recycled (Xu et al., 2019). The main reason for the low recycling rate is the obstacles in the utilization process, and government behaviors are essential to eliminate the barriers to the recycling use of building materials (Nussholz et al., 2019). The government could promote carbon emissions cut by promoting CDW reuse through policy instruments (Liu et al., 2022). Recycling CDW can significantly reduce carbon emissions, which can be seen as a reduction of implied carbon emissions from building materials (Peng et al., 2021). In addition, the last mile problem of sourcing and qualifying waste from discrete sites for central processing needs to be addressed, which could empower the CDW recycling through various intelligent technologies and concerted collaboration from multi-stakeholders coordinated by a determined government (Bao et al., 2021).

The government could exert an impact on waste recycling *via* various instruments. Kylili and Fokaides (2017) classified current policies to enhance the sustainability of building materials into three types: regulations, directives and initiatives. Some measures are critical to reducing CDW, consisting of incentives, sustainable design appraisal systems, tax breaks, and increased stringency of fiscal policies and legislative measures. Wang G. et al. (2021) analyzed the mandatory, incentive and guidance policies separately, and found that guiding policy on carbon reduction exerts the best effect when used singly, and the combination of these three policies shows a superiority effect. Hoang et al. (2021) studied the prospective supply of and demand for CDW recycling plants in Hanoi, and found that government behaviors to internalize externalities are necessary for CDW recycling. Thus, the government could readjust the price of recycled concrete aggregates by imposing raw material taxes, increasing green government procurement, and setting quality standards, thereby increasing the recycling of CDW and reducing carbon emissions. The government can also remove barriers to using circular building materials by encouraging the waste collection

TABLE 2 | Related literature about government behavior on CECI in the construction stage.

Sector	Policy classification	Representative scholars	Main content and viewpoints
Green Building	Government regulations	Steinfeld et al. (2011)	Laws
		Chen et al. (2021b)	Penalty
	Market-based instruments	Olubunmi et al. (2016)	Reward and compensation
		Zou et al. (2017)	
		Yang et al. (2019)	
		Long et al. (2020)	
		Gou (2020)	
		Saka et al. (2021)	
		Kong and He (2021)	
		He and Chen (2021)	
		Qiao et al. (2022)	
		Yang et al. (2021)	Carbon trading market
		Blackburn et al. (2020)	Promotions
		Mustaffa et al. (2021)	
Off-Site Construction	Government regulations	Luo et al. (2021)	Mandatory technical specifications
	Market-based instruments	Luo et al. (2021)	Reward and compensation
		Xue et al. (2021)	
		Yi et al. (2021b)	
		Wang et al. (2021c)	
		Gan et al. (2018)	Pilot project and guidance
		Luo et al. (2021)	

and recovery markets to recycle CDW at a higher value (Nussholz et al., 2019). Doust et al. (2021) considered regulatory change the best way to reduce CDW, and policies should focus more on front-end strategies. Government support and amenable policies can greatly determine the decision-making of on-site and off-site recycling options (Bao and Lu, 2021). The strategy combinations of government instruments could be practical to achieve CDW circular management, including 1) implementing intense governmental interventions, 2) developing a thriving CDW recycling market, 3) introducing advanced recycling technologies, and 4) enacting responsive institutional arrangements (Bao and Lu, 2020).

Generally, four processing methods are often utilized in CDW: recycling after selective demolition, advanced recycling, downcycling and landfilling (Di Maria et al., 2018). Higher quality recycling tends to demonstrate better environmental benefits. When recycling waste, even if this process is feasible, it is necessary to consider whether the carbon reduction resulting from recycling will be offset by carbon emissions from transport processes; if the latter is greater than the former, the environment will continue to be damaged (Vadenbo et al., 2017). Taking the Hong Kong case, Bi et al. (2022) established a combinatorial approach to improve the efficiency of waste collection and transportation and proposed to develop a work dispatch system like Uber or proper vehicle routing algorithms for improving waste collection efficiency and reducing carbon emissions. In addition, the landfill tax can effectively organize the landfill of CDW; meanwhile, other government behaviors are needed to promote the transfer of CDW to higher quality recycling, such as a recycled aggregates quality-certification system and natural aggregates tax increase (Di Maria et al., 2018). After assessing the effectiveness of China's CDW management policy, Yu et al. (2022) proposed that the government should strengthen the information disclosure of CDW generation, landfill and recycling and establish a unified network monitoring platform. Moreover, the government could encourage the introduction of innovative procurement models into the CDW, such as Public Private Partnership (PPP), and it is critical to devise institutions to prevent corruption and opportunistic behaviors during the process (Bao et al., 2019).

In addition to CDW, the government can also reduce CECI by spurring the recycling of other materials to produce building materials. Yan et al. (2014) suggested the government could strengthen the reuse of these sediments by relaxing the legal supervision on the treatment of dredged sediments. The government can encourage the use of them as raw materials to produce controlled low-strength material, and green building materials produced through controlled low-strength material can reduce CECI from building materials production. Karlsson et al. (2020) found that the change in Swedish waste regulation, which puts limitations on the reuse of excavation masses, can help Swedish construction supply chains reach net-zero carbon emissions.

5 CONSTRUCTION STAGE

In the construction stage, government behaviors can impact CECI by affecting the green building decisions and the adoption of off-site construction. **Table 2** presents some representative studies.

5.1 Green Building

Green building has been put forward to mitigate the significant impacts of the building stock on the environment, society and economy (Zuo and Zhao, 2014; Mattoni et al., 2018), and the core of the green building is to save all sorts of resources to the greatest extent and to minimize the pollution throughout the life cycle (Wong and Zhou, 2015). Green building presents multiple benefits to society (Olubunmi et al., 2016), and can significantly reduce CECI during the whole life cycle of the building. Hence, the green building benefits human beings living in harmony with nature and has important strategic significance (Qiao et al., 2022).

Government behaviors could internalize the positive externality of green building and avoid market failure effectively (Olubunmi et al., 2016). Government behaviors, regulation tools and promotions are critical external incentives to develop green buildings (Mustaffa et al., 2021). Gou (2020) proposed that governments can encourage the private sector to engage in green building transition through monetary incentives. The Australian government's energy policies and regulations provide incentives for promoting green buildings in Australia at different levels (Steinfeld et al., 2011). The Chinese government fines buildings that do not comply with green building rules, which could regulate the behaviors of stakeholders and avoid disorderly competition in the industry (Chen L. et al., 2021). Governments can also disseminate the value system of green buildings to the public by establishing green building ecological demonstration zones to enhance public awareness and acceptance (Blackburn et al., 2020). Government behaviors constantly interact with the stakeholders' decision-making in the green building sector (Qiao et al., 2022). Saka et al. (2021) summarized the government's reward and compensation policies to promote the development of green buildings into nine types, and determined that the government can promote the development of green buildings through one policy or a combination of more than one. Furthermore, green building technologies also face some obstacles. The lack of green building loans from banks and the cost of policy incentives are the biggest barriers to be addressed, so the government should pay more attention to the market mechanism when trying to affect the green building industry (Qiao et al., 2022).

Different policies have distinct effects on moving green buildings forward (He and Chen, 2021), and understanding and assessing the policy effectiveness and efficiency could better encourage the green-building initiative in the construction industry (Li Y. et al., 2021). Previous research indicated that the government's market-oriented voluntary incentives have a better effect than mandatory measures such as laws and regulations (Borck and Coglianese, 2009; Saka et al., 2021). When considering the effects of environmental tax, green subsidy and carbon trading market on green building technology separately, the green subsidy policy has a better effect than environmental tax. The proportion of market participants in the carbon trading market is positively correlated with adopting green building technologies, and policy combinations are more effective than individual policy instruments (Yang et al., 2021). Kong and He (2021) divided the green building policies of more than 30 provinces in China into supply-side and demand-side, and they found that compared to demand-side policies (such as housing loans and tax incentives), supply-side policies (such as land policies and floor area ratio incentives) could better promote the innovation of green building technologies. If only government subsidies are considered, the incentive effect of government subsidies to consumers (demand side) is better than that to developers (supply side); and subsidizing both will bring the highest social welfare (He and Chen, 2021). By conducting evolutionary game model, Yang et al. (2019) found that positive policy incentives may have a negative impact on the implementation of green buildings, while negative policies are proven to be effective, so government could adopt user-customized strategies. Olubunmi et al. (2016) explored the incentive effect of the government's external incentives on green building owners, and the evidence suggested that non-financial incentives are more practical in promoting green buildings when compared with financial incentives, thus the government should seek a mechanism that can determine the best level of incentives to promote the progress of green buildings.

Government behaviors vary over time and circumstances. From 2008 to 2012, green building development in China was voluntary by the private sector; In 2013, the central government made the development of green buildings a mandatory requirement for government investment projects through a series of targeted policies, which contributed to an exponential growth in the number of green projects (Gou, 2020). Nevertheless, there were many opportunistic behaviors in the process: some developers falsified data on green grades, and some sellers made false claims about the green performance of their products in order to capture excess profits, which also reduced consumers' willingness to pay (Qiao et al., 2022). In addition, financial subsidies account for more than 50% of the Chinese government's incentive policies for green buildings (Zou et al., 2017), which has put enormous pressure on the national finances. Therefore, the government should adjust its incentive policies to adapt to the market development stage of green buildings and determine the optimal subsidy intensity in line with the actual situation of different stages, which will help the market achieve an optimal equilibrium (Long et al., 2020). More specifically, understanding collaboration networks in construction carbon reduction could be helpful to government agencies for facilitating built environmental transformation and multi-disciplinary collaboration (Wang G. et al., 2021).

5.2 Off-Site Construction

Off-site construction (OSC) originates from manufacturing (Mao et al., 2015), which means that the builder produces a part of the components required for the construction in a controlled environment and then transports them to the construction site for assembly (Yi et al., 2021b). The main advantages of OSC encompass faster construction (Gan et al., 2018), lower cost (Polat, 2008), ability to reduce CECI and construction waste (Mao et al., 2013), and lower labor requirements (Jaillon and Poon, 2008). However, due to market share and technical integration, OSC is currently not widely used. In China, the gross floor area of projects adopting OSC in 2020 is only 630 million square meters, accounting for only 20.5% of annual new buildings (Xue et al., 2021). In order to achieve the carbon neutrality goal, the Chinese government needs to promote the widespread use of OSC through effective policies (Luo et al., 2021). Currently, policymakers worldwide are working to push OSC promotion by developing multiple policies (Weisheng and Hongping, 2012; Guribie et al., 2021). In summary, the current mandatory instruments adopted by the government to promote OSC include legal constraints and mandatory technical specifications, and market-based instruments include floor area ratio (FAR) awards, financial subsidies, land support, financial support, tax subsidies, and pilot project assistance (Jiang et al., 2019; Pham et al., 2020).

Luo et al. (2021) divided the government's policies to promote OSC into five forms: incentives, standards, regulations, guidance and initiatives. In China, regulations are the easiest and most effective way to promote OSC but are often ignored by policymakers; policymakers have created various incentives to promote OSC promotion, whereas they are rarely used because they impose additional financial burdens on governments. Luo et al. (2021) concluded that the Chinese government should further optimize policy tools and provide financial support. Using partial least-squares path analysis, Xue et al. (2021) measured the impact of three types of policies (demand-side, supply-side and environmental) on the implementation of OSC by developers. The result illustrated that environmental policies perform a more significant promotion effect on the implementation of OSC, while supply-side and demand-side policies have no direct effect on the implementation of OSC by developers. Hence, the government should optimize the policy system and implement a combination of mandatory policies and market-based instruments (Xue et al., 2021; Hussain and Lee, 2022).

Using social network analysis, Gan et al. (2018) analyzed 15 types of stakeholders' power status on 13 types of barriers and identified that the government and developers exert the most significant impact on OSC execution. Therefore, the government should take measures to endorse stakeholder collaboration to overcome existing barriers, such as the dominant conventional project processes and the lack of expertise. As a market-based instrument, government subsidies can support the promotion of OSC, and policymakers need to pay attention to the rationality of subsidies (Yi et al., 2021a). Based on a three-stage Stackelberg game framework, Yi et al. (2021b) found that unreasonable government subsidies for OSC would reduce the use of precast concrete in construction and thus increase carbon emissions from transporting precast concrete. Grounded on an evolutionary game model, Wang H. et al. (2021) analyzed the interactive effect of the behaviors of government and developers, and proposed that the government should establish an institutional framework that includes reputational rewards and financial incentives for developers. The government should strengthen public education to mitigate negative perception, and cultivate OSC professionals by guiding school-enterprise cooperation and establishing education bases.

6 OPERATION STAGE

The operation activities of the building mainly include lighting, cooking and the maintenance of heating, ventilation, and air conditioning (HVAC) systems (Fan et al., 2018), which generate a lot of operational carbon (Hacker et al., 2008). In winter, building operation accounts for about 24% of CECI due to coal consumption and power use of buildings (Zhang and Wang, 2016). The contribution of the building operation will increase to 40% if the accommodation and offices on the building site are taken into account (Wu et al., 2019). Wu et al. (2019) argued that CECI mainly comes from the manufacturing of building materials and the operation of buildings, accounting for 58 and 40%, respectively. In China, carbon emissions from building operations increased from 0.67 gigatons in 2000 to 2.11 gigatons in 2018, accounting for 21.9% of China's total carbon emissions (Chen M. et al., 2022). From the experience of China and the United States, government guidance is the most considerable motivation for carbon reduction in building operations (Zhang S. et al., 2022). At the same time, for built roads and other infrastructure, the government should concentrate more on maintenance rather than repair, which will have a better effect on carbon emission reduction (Ruiz and Guevara, 2020).

Government behaviors can impact CECI in the operation stage by affecting energy conservation behaviors and green retrofit decisions. **Table 3** exhibits some representative literature.

6.1 Energy Conservation and Emission Mitigation

Energy-conservation and emission-mitigation (ECEM) are essential to reduce carbon emissions in the operation phase. Government intervention can help ECEM establish structured processes to improve energy use efficiency and raise social awareness (Ruparathna et al., 2016).

The current research on carbon emission reduction of buildings in the operation phase mainly focuses on residential and commercial buildings. Government ECEM strategies in the residential sector include mandatory, information, and economic intensive (Ma et al., 2019b). The mandatory strategy includes formulating energy-saving standards in the residential sector, the information strategy includes energy efficiency labels and stepped electricity prices, and the intensive economic strategy involves special government funds and financial subsidies. Similarly, Azevedo et al. (2013) compared these three energy policies as sticks, tambourines, and carrots. For commercial buildings, it is very effective for local governments to develop a comprehensive energy consumption detection platform and provide necessary administrative and financial support (Li et al., 2022). Ma et al. (2019a) noted that the government's firm and continuous commitment to building energy conservation and emission reduction and the promotion of the large-scale use of renewable energy in civil building operations provide a strong guarantee for the successful implementation of government energy conservation regulations. Coal still accounts for 70% of all energy and other consumption (Xu et al., 2014); therefore, the government can significantly reduce CECI by advocating using clean energy such as natural gas to replace coal (Wu et al., 2019). Government should formulate a more feasible low-carbon or zero-carbon roadmap, promote the electrification of urban and

TABLE 3 | Associated literature about government behavior on CECI in the operation stage.

Sector	Policy classification	References	Main content and viewpoints
Energy conservation and emission mitigation	Government regulations	Yao et al. (2005) Azevedo et al. (2013) Delmastro et al. (2015) Ma et al. (2019b)	Mandatory standards
	Market-based instruments	Azevedo et al. (2013) Ruparathna et al. (2016) Ma et al. (2019b) Wu et al. (2019) Han et al. (2021) Chen et al. (2022a) Zhang et al. (2022a)	Information strategy
		Azevedo et al. (2013) Fan and Xia (2017) Ma et al. (2019b) Li et al. (2022)	Economic intensive strategy
Green retrofit	Government regulations	Tan et al. (2018) Liu et al. (2020) Tan et al. (2021)	Direction-based policies
		Tan et al. (2018) Liu et al. (2020) Tan et al. (2021)	Regulation-based policies
	Market-based instruments	Tan et al. (2018) Iralde et al. (2021) Tan et al. (2021) Kim et al. (2022)	Financial support policies
		Jagarajan et al. (2017) Tan et al. (2018) Tan et al. (2021)	Evaluation-based policies
		Tan et al. (2018) Bobrova et al. (2021) Tan et al. (2021) Alabid et al. (2022)	Knowledge and information policies

rural residential consumption and accelerate electricity decarbonization in society to better develop the decoupling effect in Carbon Kuznets curves to hit the carbon neutrality goal (Chen M. et al., 2022).

The Chinese government introduced a series of building energy standards early in the 1980s, but the implementation of the standards at that time was slow (Yao et al., 2005). Between 2006 and 2015, in the field of residential ECEM, the Chinese government has formulated more than eighty policy documents, over ten relevant codes and acts, and at least fifty mandatory standards, which made remarkable achievements in reducing carbon emissions in China's residential sector (Ma et al., 2019b). The China Act on the Energy Efficiency of Civil Buildings promulgated by the Chinese government in 2008 has made significant contributions to the ECEM of Chinese civil buildings, such as the unprecedented development of the application of renewable energy in the building operation stage (Ruparathna et al., 2016), and the promotion of the establishment of energy conservation policies system of buildings (Han et al., 2021). At the same time, the introduction of the central government's national strategy and financial incentives, such as the "Solar Energy Roof Plan" in 2009 (Fan and Xia, 2017), made the geothermal and solar application areas of civil buildings in China reach 478 and 476 million square meters respectively at the end of 2016 (Ma et al., 2019a). Prior research recommended that the Chinese government continue to implement energy policy within an appropriate policy framework, which will help China reduce energy consumption by 850–4005 PJ in 2030 compared to a scenario where no policy is adopted (Delmastro et al., 2015).

While each country is establishing its policy system for carbon emission reduction in the building operation field, it is also crucial to conduct international technical cooperation RandD and experience sharing sessions on carbon emission reduction in the construction industry (Zhang S. et al., 2022). There are regional differences in the carbon emissions of building operations due to differentiation in economic development levels and climate conditions (Wang Z. et al., 2021), so the government needs to take different carbon emission reduction measures to respond to local conditions when intervening (Li H. et al., 2021). The government has achieved excellent outcomes in promoting technological advances in ECEM, but efforts to help build energy habits and develop low-carbon lifestyles for building users are somewhat inadequate (Ruparathna et al., 2016). The usage behaviors of occupants in buildings will significantly alter building energy consumption and carbon emissions. The government should fully consider the impact of occupant behavior when issuing energy policies, as misunderstood and oversimplified occupant behavior will bring new problems (Hu et al., 2020).

6.2 Green Retrofit

Compared with green buildings mainly oriented to creating increments, green retrofit aims to improve the energy and resource efficiency of existing buildings during the operation phase of the building (Liu et al., 2020). Green retrofit is anticipated to trigger global energy and resource efficiency effectively, thereby reducing carbon emissions (Ruparathna et al., 2017).

Government policies are of great importance for green retrofit (Baldwin et al., 2018), and government behaviors are the pivotal drivers for green retrofit development and carbon reduction (Liu et al., 2020). Many countries have carried out corresponding measures to promote green retrofit, such as the Green Deal in the UK, the Building Retrofit Energy Efficiency Financing scheme in Singapore and the Energy Policy Act in the United States (Liu et al., 2020). Tan et al. (2018) divided more than 500 policies in more than 29 countries worldwide into six categories: direction-based policies, regulation-based policies, financial support policies, organization and professional training policies, evaluation-based policies and knowledge and information policies. It is argued that different policies can play particular roles at different stages.

Direction-based policies, such as plans, directives or frameworks, can provide long-term direction for the market, reflecting the macro trend of market development. Government policies, such as the EU Energy Performance of Buildings Directive 2018/844, demonstrate policymakers' determination to promote the green transformation to industry stakeholders and form the basis of all policies (Liu et al., 2020). Regulation-based policies refer to government laws and regulations. Common evaluation-based policies include government-issued labels and green ratings for projects, such as the Green Building Evaluation Label in China, the Eco-Management and Auditing Scheme in the EU and the Leadership in Energy and Environmental Design (LEED) in the US. The government's assessment helps identify the potential for renovation of old buildings, paving the way to initiating subsequent laws and financial policies (Jagarajan et al., 2017).

Financial support policies, such as government subsidies and tax exemptions, could trigger the action of green retrofit implementers. The investigation of Iralde et al. (2021) on the energy transformation of residential buildings in Spain indicated that government funding currently accounts for only 8% of all necessary investments, far from what is currently available, and the fragmentation and complexity in policy implementation reduce its global impact. In addition, the green loans provided by the government also exert a significant impact on the development of green retrofit. With the increase in supporting interest and carbon tax rates, the government and building owners will take more active actions (Kim et al., 2022).

Organization and professional training policies, such as RandD, are beneficial for developing new green retrofit technologies. Professional industry associations and experienced experts help improve the technical level of green renovation skills (Tan et al., 2018); thus, it is vital to establish an effective green transformation market. Knowledge and information policies can help to increase stakeholder awareness of green retrofit. The government should raise public awareness of the importance of green retrofit in reducing carbon emissions by organizing workshops and training programs with end-user participation to make the public part of the green retrofit decision-making process (Alabid et al., 2022). In the early stages of green transformation decision-making, providing information to homeowners through non-expert networks is essential to advance the decision-making process (Bobrova et al., 2021).

According to the promotion effect of different policies on green retrofit technology, Tan et al. (2021) further divided the six green retrofit policies into three priorities. Among them, direction-based policies, financial support policies and knowledge and information policies are policies at tier one. These policies can directly affect air conditioning and lighting, which account for 40% of a building's total electricity consumption and play the most critical role in reducing CECI.

However, most studies only focus on a single policy and its impact, and studies on the impact of multiple policy combinations are lacking in current research (Liu et al., 2020). There is no one solution fits all (Alabid et al., 2022), so existing policies toward green retrofit do not apply in all cases.

7 CONCLUSIONS AND FUTURE RESEARCH

This study reviewed the CECI research domain and corresponding government behaviors by employing the bibliometric analysis and introducing an analytical framework of the transmission path of government behaviors towards CECI. The result indicated that government instruments affected the CECI through three critical stages and seven key subsystems during the life cycle of construction carbon emissions.

Based on systematic summarization of government behavior on CECI, this paper found several gaps to be addressed in existing studies. First, most studies focus on the impact of a single policy, while few concentrate on the impact of policy combinations on CECI. Moreover, existing research is more about the impact of government behaviors on a particular part of the building life cycle. However, in practice, some government behaviors can affect the whole life cycle of the building. Given these, this paper puts forward some suggestions and prospects for future research.

Firstly, government policies are always characterized by a combination form, including non-exclusive economic incentives and mandatory administrative measures. Compared with a single policy, policy combinations perform excellent superiority. Wang G. et al. (2021) found that the combination of the mandatory, incentive and guidance policies shows tremendous advantages for waste recycling. Saka et al. (2021) summarized the government's reward and compensation policies to promote the development of green buildings into nine types, and proposed that the government can promote the development of green buildings through a combination of different policies. When considering the effects of environmental tax, green subsidies and carbon trading market on green building technology, Yang et al. (2021) found that policy combinations are more effective than individual policy instruments. Liu et al. (2020) proposed that studies on the impact of multiple policy combinations are lacking in prior studies on green retrofit. Therefore, the interaction and connection between different government instruments may need to be considered when exploring the impact, rather than simply applying a so-called mature mathematical model to try to explain the whole picture. The coupling effects of various governmental instruments should be incorporated to maximize their function of carbon reduction in the building sector. Regarding the research methodology, the fuzzy-set qualitative comparative analysis (fsQCA) techniques and Necessary Condition Analysis (NCA) (Ragin and Strand, 2008) could be conducted to investigate the impact path of government instruments.

Secondly, the life cycle of buildings is very long, and many policies may not only affect one stage. For instance, selecting unreasonable low-carbon building materials seems to reduce carbon emissions in the building materials production stage, but it may increase energy consumption and carbon emissions in the construction operation stage. Previous studies have investigated carbon emissions throughout the life cycle of buildings (Hong et al., 2015; Wong and Zhou, 2015; Wu et al., 2019; Ruiz and Guevara, 2020). However, there is less literature focusing on the effects of government behaviors, and the integrative role of government behavior on the CECI is still ambiguous. Therefore, it is valuable to disclose the mechanism for government behaviors in decreasing carbon emissions from the whole life cycle of buildings. Meanwhile, positive and negative performance should be equally noticed in the assessment of policy effectiveness and efficiency, and the negative externality of government behaviors needs more attention, such as dishonest behavior of carbon emission information disclosure in construction companies. More importantly, it needs to consider the multiple stakeholders in implementing the instruments to reduce the transaction cost, such as information disclosure, knowledge sharing and decision-making costs.

Thirdly, intensive work could be utilized in more innovative areas to reduce CECI, including zero energy building (ZEB), megaproject carbon neutrality and community carbon neutrality. More and more researchers have begun to focus on ZEB and passive houses. The passive house is regarded as a critical strategy for the low carbon economy in Europe (Piccardo et al., 2020), and ZEB is an essential pillar in achieving carbon neutrality goals, but its share in existing buildings remains low (Zhang et al., 2021). Concerning the current assessment of the mega project, the technical factor is the most important factor considered. In the future, more attention should be paid to the carbon emissions generated during the construction and operation of the mega project. As the smallest unit of the city, carbon reduction in the community may receive more attention. Infrastructure, application scenarios and lifestyles in communities are the key factors affecting CECI in cities during the building operation stage. At the infrastructure level of the community, the government can influence the installation of photovoltaic power generation devices and the upgrading of building energy efficiency through the establishment of special development funds for building energy efficiency. Meanwhile, the government's advocacy and subsidies can help communities make better use of public building space in the community for roof greening or vertical greening. In terms of application scenarios and lifestyles, influencing the behavior of building occupants can contribute to reducing CECI, but research in this field is currently inadequate (Ruparathna et al., 2016). Moreover, the government should also thoroughly consider the behavior of building users at the micro level when formulating relevant environmental regulations, as misunderstood and oversimplified occupant behavior might cause problems in policies (Hu et al., 2020). Therefore, establishing an effective community low-carbon living system can help reduce CECI. In the future, more research can focus on these fields and contribute to the realization of carbon neutrality goals and the sustainable development of humankind. Furthermore, more international collaboration networks on emerging Frontier technologies and patterns should be summarized and explored to promote the carbon reduction action in the construction industry.

This study attempts to investigate government instruments in the carbon reduction in the construction industry from the whole life cycle perspective by bibliometric analysis and systematic review. However, several limitations in this research should be recognized. First, the study is entirely sourced from the core database of WoS. Though WoS is widely conducted in literature review articles for its authoritative source, some important papers in other databases might be overlooked. Moreover, this study did not exhibit co-author and co-citation networks since prior studies on government behavior in CECI are relatively few and dispersed. Furthermore, the focus of government instruments in CECI could vary from different cultures and regions, which has been ignored in the study. Understanding the characteristic differences in CECI in different regions could help local policymakers formulate appropriate emission reduction policies in the long term. Further study could consider the differentiation among the countries/regions to provide insightful ideas for reducing CECI.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

DT and XG contributed to the conception and design of the study. XG collected the data, analyzed and wrote the first draft of the manuscript. DT and ML wrote the sections of the manuscript. DT provided the funding support for this study. All authors contributed to manuscript revision, read, and approved the submitted version.

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Decision criteria and intelligent decision method for tunnel excavation scheme selection considering carbon emissions

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The tunnel construction process is accompanied by high resource consumption and non-negligible greenhouse gas emissions. Reducing the carbon emissions from this process is an issue that should be considered in the decision-making stage. For tunnel construction using the drill-and-blast process, selecting a reasonable excavation scheme is a feasible method for reducing carbon emissions. This paper proposes an evaluation index system that takes into account the stability of the tunnel construction process and the reasonable assessment of carbon emission levels. For various scenarios with different focus on stability requirements, theoretical deductions are used to filter out the key indicators that should be used as assessment items. For the determination of carbon emission assessment indicators, this study is guided by the life cycle theory, and in the determined calculation boundary, the reference of previous projects and expert opinions are selected as the item source to fill the unfavorable situation in which the carbon emissions of different excavation schemes cannot be accurately calculated because of the lack of bills of quantities in the engineering decision stage. This paper also proposes an intelligent decision method based on a support vector machine to better complete the task of calculating and ranking the utility of excavation schemes to adapt the proposed multi-factor parallel evaluation system. Finally, the proposed decision indicator system and decision method were applied to the selection of the excavation scheme in an engineering case, and reasonable and realistic scoring results were obtained.

KEYWORDS

carbon emission assessment, tunnel engineering, life cycle theory, support machine vector, excavation scheme

Introduction

The choice of tunnel construction excavation method based on the drill and blast method determines whether the tunnel construction can meet the required technical and economic demands. Different excavation methods have different engineering effects in different rock conditions and other realistic situations; the choice of the appropriate excavation method will have a positive effect on the safety as well as economic aspects of the project; the current common method of comparative selection work is based on pure numerical simulations, or numerical simulations combined with theoretical calculations, field monitoring, and experiments are used to compare stability indicators such as stress distribution and deformation conditions, either individually or independently of each other: Gong et al. (2009) used finite element numerical simulation to analyze vault displacements, surface settlements, intermediate rock column stresses, and stability of surrounding rock in three different excavation schemes. Jiang et al. (2012) used dynamic numerical simulation to sort double drifts method, CD method and CRD method, and select the best excavation method from them for the evaluation items of vault subsidence, horizontal displacement of intermediate rock column, horizontal displacement of surrounding rock and variation of plastic zone in surrounding rock. Li et al. (2014) used finite element numerical simulations to compare and analyze the feasibility of the CD method and the three-bench seven-procedure excavation method from the perspectives of the surrounding rock deformation, stress field changes and initial support stresses in the corresponding projects. Mou et al. (2017) compared the bench method, CRD method and core soil method from the perspectives of arch top settlement, arch bottom uplift, horizontal convergence and arch internal force distribution; Jiang et al. (2018) conducted a comprehensive calculation and comparison from surrounding rock to support system from the perspectives of arch top settlement, arch bottom uplift, side wall convergence, surrounding rock stress, initial support internal force, and second lining internal force for the CD method and two types of bench methods, the calculation and comparison of the three methods are carried out from the perspective of the surrounding rock to the support system. In some studies, numerical simulations were combined with field monitoring and testing and complemented each other to achieve more comprehensive and realistic analysis results (Liu and Zhang, 2011; Zhou et al., 2013; Hou et al., 2017).

In addition to the evaluation of independent stability indicators for the comparison and selection of tunneling methods, studies related to the selection of methods using comprehensive evaluation theory or optimization decision theory also exist (Zhang et al., 2007; Golestanifar et al., 2011; Bi et al., 2013; Zheng, 2016; Wu et al., 2020; Wu et al., 2021). But they are basically case-by-case special applications, none of which is comprehensive and general evaluation guidelines have not been formed. On the other hand, most of the evaluation methods used in the traditional evaluation index system require the calculation of combined weight coefficients. When the evaluation index system is complex, an excessively large weight matrix will cause calculation difficulties, so we can try to propose a calculation model without weight coefficients to simplify the evaluation of the scheme under complex indexes. While the use of intelligent methods for decision making has emerged in the last 30 years (Sellak et al., 2017; Fu et al., 2020) and its essence is the adaptive identification and generation of patterns between decision elements and decision options, which has the underlying characteristic of not relying on weights.

At the same time, the traditional process of selecting engineering solutions is too sparse to consider carbon emissions, but Miliutenko et al. (2012) point out that the greenhouse gas emissions caused by tunneling are much larger than those of other engineering constructions, and under the trend of increasingly significant attention to carbon emissions by governments and organizations (Liu et al., 2022; Xia et al., 2022), research work on the qualitative, quantitative, and control of carbon emissions in the construction process is gradually being carried out: Guo et al. (2020) summarized the carbon emission calculation boundary and existing calculation methods for tunneling projects; Ahn et al. (2010) conducted a carbon footprint tracking and quantification study using the direct carbon emission calculation method for the carbon emissions of the TBM method portion of the North Edmonton Public Health Trunk Line Tunnel in Canada; Morris et al. (2016) conducted a study on the Hong Kong Cross-Harbor Tunnel project and summarized the set of factors to be considered in the selection of the method during tunnel construction, including application demand factors, site geotechnical constraints, length and section use factors, and ecological and environmental impacts. These studies provide a basis for further investigations of carbon emission patterns during tunnel construction.

In addition to the differences in applicability under different geological conditions, the environmental impact factors, such as carbon emission levels, are also very different among the different methods. Therefore, for future tunnel excavation scheme selection, it is necessary to introduce reasonable carbon emission evaluation indicators and integrate them with traditional indicators, and to adopt more efficient evaluation criteria and calculation methods to adapt multi-attribute decision models with hierarchical relationships. Therefore, an intelligent evaluation method based on support vector methods, a machine learning-based approach to pattern recognition and mapping, was proposed to solve the scheme ranking problem, and feasible solutions were obtained for selected engineering cases.

Analysis of stability criteria

Criteria for assessing stability of surrounding rock

When considering the idealist scheme for the main purpose of stabilizing the excavation process, the grade and specific nature of the surrounding rock, as well as other original environmental factors, are the primary factors in the scheme decision. The selection of a reasonable evaluation indicator system to comprehensively, jointly, and effectively assess the mechanical behavior and deformation of the surrounding rock before and after excavation using various methods is key to accurately determining the most appropriate construction scheme.

Due to the existence of the three-dimensional effect of the excavation face, the rock at the front end of the excavation face can maintain temporary stability; under the coupling effect of the bell-shaped constraint along the tunnel axis direction section and the circular constraint on the plane section perpendicular to the axis (Sun and Zhu, 1994), the convergence deformation of the section within a certain distance from the current excavation palm face is suppressed, in order to describe the effect more intuitively and accurately, the displacement release coefficient is introduced, that is, the displacement of point p pointing to position l on the section of the surrounding rock at horizontal distance z from the excavation face and the displacement ratio of the corresponding point at infinity of the coaxial line pointing to the same parallel position, it is denoted as $\lambda l, z, p$; The study observes that the three-dimensional constraint effect no longer exists after 3 times the tunnel span from the excavation face, i.e., when $l = 3D$, at which time the $\lambda l, z, p = 1$; With the help of displacement release coefficients, Kielbassa and Duddeck (1991) transformed the three-dimensional problem of spatial constraint effects into an axisymmetric stress-strain problem in the two-dimensional plane, and pointed out that the radial stress σ_r in the surrounding rock after excavation is twice the initial hydrostatic stress before excavation, and that σ_r is a convergence curve consistent with the deformation of the longitudinal section, and that the radial stress in the surrounding rock is balanced by the stress $\sigma_0(z)$, which is released with the convergence deformation, and the virtual support force $p(z)$, which is calculated equivalently as follows:

$$\boldsymbol{\sigma}(z) = \boldsymbol{p}(z) + \boldsymbol{\sigma}_0(z) \tag{1}$$

with the introduction of the displacement release coefficient, the above equation can be rewritten as

$$\boldsymbol{p}(z) = [1 - \boldsymbol{\lambda}(\boldsymbol{r}, z)]\boldsymbol{\sigma}(z) \tag{2}$$

where is the distribution of the virtual support force along the excavation axis at the excavation surface, note $[1 - \lambda(r, z)]$ as the virtual support coefficient, combined with the calculation results of the displacement release coefficient of the full-face method provided by (Sun and Zhu, 1994), the virtual support force distribution is shown as follows:

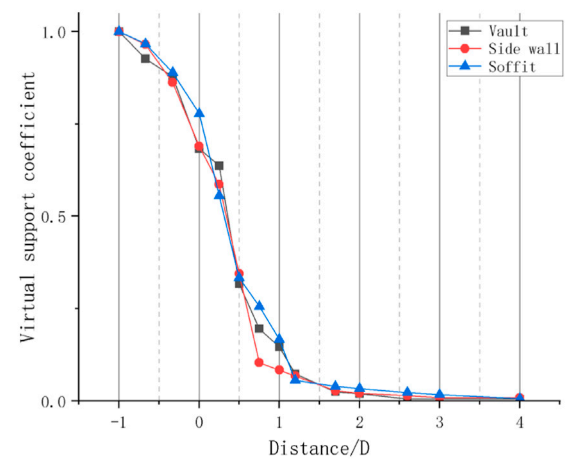

FIGURE 1
Virtual support force distribution in tunnel space.

It is not difficult to find from Figure 1 that the maximum radial convergence deformation occurs at a certain distance from the excavation face; therefore, in the monitoring and simulation process, the location of monitoring points or numerical calculation of the value of the cross-section should be elected at a distance of more than three times the diameter of the palm face. Therefore, for the need for a comprehensive and full assessment, it should be clear that according to the division of the critical area, the stability of the excavation face, and the radial stability of the section of the two elements needs to be judged independently, and the stability of the excavation face is not the only element of the stability of the excavation process.

The stability of the excavation face can be further discussed, and the excavation face can be further divided into palm, side wall, and vault faces. For weak and fractured rocks, the excavation palm face often cannot hold itself and undergoes large deformation and fragmentation, and it is necessary to pay attention to the convergence deformation of the palm face if it is not clear whether the corresponding work method will cause serious destabilization problems, such as collapse.

The calculation of the mechanical effect is mainly performed by numerical simulation based on finite element (Zhao, 2012; Real et al., 2015; Song et al., 2019), discrete element (Xiang et al., 2018; Wu et al., 2020; Chen et al., 2022) or the finite difference method (El Omari et al., 2021; Zaheri et al., 2021; Bai et al., 2022), The distribution of the plastic zone of the surrounding rocks is evaluated against the calculation, but most of the cases are limited to direct comparison, and the reasons for the appearance of the plastic zone and the influence of the plastic zone on the calculation results were not analyzed, which sometimes caused some deviation in the process of evaluating the excavation

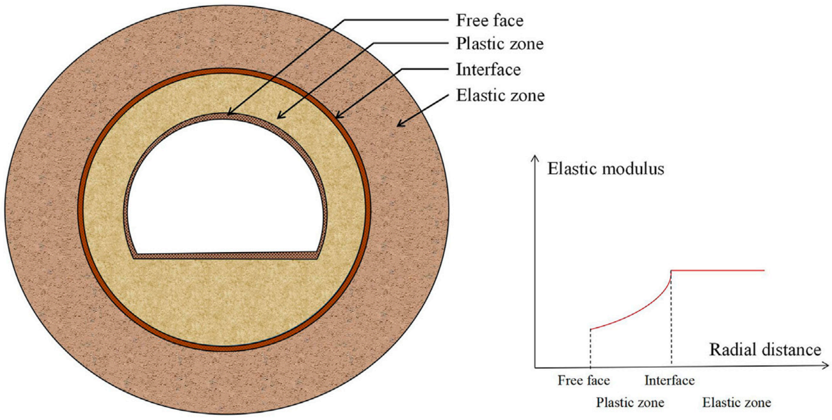

FIGURE 2
Elastic modulus distribution of the annular elastic-plastic zone of the surrounding rock in excavated tunnel.

scheme only by numerical simulation. Criteria for assessing stratigraphic stability. The stress redistribution caused by excavation is the main reason for the plastic zone, but the perturbation of the surrounding rock during excavation can also cause the plastic zone of the adjacent rock to expand further, and the existence of cases (Song et al., 2019) can confirm this. The elastic modulus of the surrounding rock in the plastic zone is weakened, which requires the selection of the physical property parameters of the surrounding rock for simulation work to be more refined, and the modulus of the disturbed rock body needs to be discounted if the corresponding plasticity criteria are selected. This simplification can be avoided if the corresponding plasticity-reduction damage criterion is selected; otherwise, it can cause considerable differences between the calculated results and actual effects. It is worth mentioning that the means of reducing the geotechnical strength parameters are more commonly used to indirectly discover the potential structural risks of underground works; this reduction is also desirable in the simulation process of direct demonstration of tunnel construction flows or final results.

During tunnel excavation, the elastic modulus, cohesion, and shear angle of the surrounding rock in the plastic zone change to some extent (Zhang et al., 2016), but given that changes in different parameters have different effects on the deformation of the tunnel in each zone, that is, they have different sensitivities to the results, it is not necessary to focus on all material parameter changes. According to relevant studies (Huang et al., 2008; Wang and Chen, 2012), the sensitivity of the elastic modulus to convergence deformation and settlement is higher than that of cohesion, shear angle, and Poisson's ratio, and it is feasible to correct the elastic modulus only for the plastic zone. There are two common ways to describe the elastic modulus variation in the plastic zone: pressure-dependent elastic modulus (PDM), which considers the change in the elastic modulus of the plastic part of the surrounding rock to be based on the hydrostatic pressure σ_3, and radius-dependent elastic modulus (RDM), which considers the change in elastic modulus to be based on the radial distance r.

Because both the stress redistribution in the surrounding rock and the disturbance during excavation are closely related to the distance, and σ_3 near the tunnel is essentially a function of r, the pressure-dependent elastic modulus can also be regarded as a special form of the radius-dependent elastic modulus; therefore, the model derived from the radius-dependent elastic modulus expresses the progressive change in the elastic modulus of the surrounding rock more universally from the theoretical level to the practical application scenario level, considering the expression for the elastic modulus proposed by Ewy and Cook (1990) as an example:

$$\boldsymbol{E}(\boldsymbol{r}) = \boldsymbol{E}_r(\boldsymbol{r}/\boldsymbol{r}_i)^n,\ \boldsymbol{n} = \frac{lg(\boldsymbol{E}_i/\boldsymbol{E}_r)}{lg(\boldsymbol{R}/\boldsymbol{r}_i)} \quad (3)$$

where E refers to elastic modulus of surrounding rock, E_r is the value of $E(r)$ when $r = r_i$ (r_i is the distance between from the central point of the cross-section to the tunnel's free face), that is, the elastic modulus on the tunnel's free face along the axis r_i; and R is the distance from the tunnel axis to the interface of the elastic-plastic zone.

The distribution of the annular elastic-plastic zone of the surrounding rock is as follows:

For the above equation, assume that $n < 0$, that is, the elastic modulus inside the plastic zone is smaller than the elastic modulus of the free face, and then substitute the calculation will come to the opposite conclusion, which means $n \geq 0$ is correct, and further it is not difficult to find that if $n > 0$, the elastic modulus of the plastic zone is constantly smaller than the elastic modulus of the interface of the elastic-plastic zone, and reach the minimum and maximum value in the free face and the interface of the elastic-plastic region, respectively (As shown in Figure 2); According to the above rules, in the process of numerical simulation, the criteria of discounting the material parameters into the plastic deformation stage should be introduced as much as possible, and if the applicable constitutive model cannot be introduced, the equivalent elastic modulus change in the plastic zone should be considered to be directly discounted, and when the shape of the section is more regular, the above expression of elastic modulus can be introduced to calculate directly, and those cases with situ sampling or real-time monitoring conditions can collect samples and data to make combinational correction. It can be seen that the plastic zone, as an indicator to be considered in the process of scheme comparison, is not only for direct comparison, but also for the excavation schemes with large disturbances of the surrounding rock, and the analysis of the area of the plastic zone of the section and the evolution process with the flows can be more intuitive and clearer for analyzing the final impact of the disturbance.

When it comes to the specific excavation scheme selection, for the judgement criteria of the surrounding rock deformation, the most used indicator is the vault settlement (Liu and Zhang, 2011; Hou et al., 2017), followed by the arch foot or other free convergence deformation. There are also some engineering cases (Gong et al., 2009) because of the special nature of the rock that needs to investigate the longitudinal displacement of the arch foot or arch bottom and to be adjusted in time, and the calculation and investigation of the surrounding rock stress mainly rely on stress nephograms, especially in cases with special structures Sun as the center columns.

In summary, when considering the judgement criteria for evaluating the applicability of each excavation scheme in terms of rock stability, it is possible to consider the selection of indicators, such as vault settlement, arch foot settlement, or other parts of the headroom convergence, plastic zone, and stress nephograms.

Criteria for assessing the surface settlement

For shallow buried tunnels built in urban areas, there is less tolerance for ground settlement caused by their engineering behavior because they are often adjacent to a large number of buildings and other infrastructure, and it is necessary to establish and refine the evaluation indicators of alternative excavation methods based on the examination of the causes of ground settlement. The main methods for the quantitative assessment of ground deformation caused by underground excavation are the Peck method and stochastic medium method (SMM).

The Peck method was first proposed by Peck (1969) based on the analysis of a large amount of actual measurement data, and it has been refined by other scholars since then, and eventually the modified peck equation for urban underground tunnelling emerged, as well as the analysis of the process mechanism corresponding to the equation (Rankin, 1988), which is a near-complete answer to the question of the characteristics of the Peck method, and how to tailor it to fit with different geotechnical conditions.

While the stochastic medium method (SMM) was first proposed by Litwiniszyn (1958), which were first applied in mining engineering and then extended to the analysis of engineering problems in urban underground space construction (Han and Li, 2007). Together with the Peck method, they have become two common methods for the study of surface settlement patterns. The evolution and control factors of ground settlement and surface deformation induced by tunnel excavation were analyzed by deriving their unified forms and comparing their similarities and differences.

The modified Peck method (Rankin, 1988), which is widely used today, describes the ground settlement trough cross-section as a normally distributed curve, and the model expression is:

$$S(x) = S_{max} \exp\left[-\left(\frac{x}{\sqrt{2}i}\right)^2\right] \tag{4}$$

where S_{max} is the global maximum settlement at the position of the central axis of the tunnel section and i is the horizontal projection distance from the central axis to the point of inversion of the fitted normal distribution curve. If the stratigraphic loss rate used to assess the difference between the excavated soil volume and the structure space volume is introduced, the above equation can be rewritten as

$$S(x) = \frac{AV_l}{\sqrt{2\pi}i} \exp\left[-\left(\frac{x}{\sqrt{2}i}\right)^2\right] \tag{5}$$

where V_l is the stratigraphic loss rate, A is the ratio of the settlement trough cross-section to the design cross-section of the underground space structure within a linear metre, and AV_l is the area lost per linear metre of the underground space structure cross-section.

Stochastic medium theory considers that the process of ground subsidence and displacement caused by the excavation of underground space is the superposition of the subsidence effect of the excavation of infinite micro-units. The complexity of geotechnical parameters and mechanical behavior makes micro-unit a "stochastic medium," so the settlement performs a random nature and takes a micro-unit analysis; when it is in a state of unconsolidated undrained and complete collapse, the longitudinal displacement of any point on the upper surface plane is:

$$S_e(x) = \frac{1}{r(z)} \exp\left[-\pi\left(\frac{x}{r(z)}\right)^2\right] d\xi d\eta \tag{6}$$

The integral equation of it is as follows:

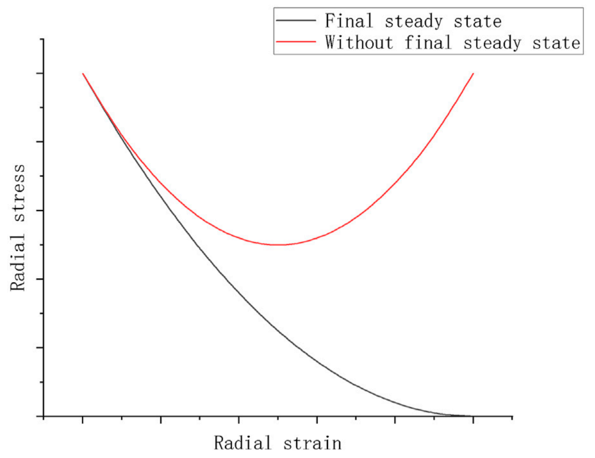

FIGURE 3
GRC curves for two different stable state of tunnel excavated section.

$$S(x) = \iint_{\Omega-\omega} \frac{1}{r(z)} \exp\left[-\pi\left(\frac{x}{r(z)}\right)^2\right] d\xi d\eta \tag{7}$$

where $r(z)$ is the major influence radius of the micro-unit in the plane of depth z after the excavation.

Generally, it is considered that the major influence area of the settlement trough is a funnel shape centered on the tunnel, and the expression of the major influence area of the settlement trough (Knothe, 1957) is as follows:

$$r(z) = z/\tan\beta \tag{8}$$

where β is the main influence angle of the upper surrounding rock.

In accordance with the full radial convergence form of the tunnel proposed by Han and Li (2007), for integration over the collapsed area, the surface settlement expression can be derived as

$$S(x) = \iint_{\Omega-\omega} \frac{\tan\beta}{\eta} \exp\left[-\frac{\pi \tan^2\beta}{\eta^2}(x-\xi)^2\right] d\xi d\eta \tag{9}$$

By definition, Eq. 5 is the integral of the fully collapsed micro units in the fully convergent collapsed region, and Eq. 5 can be rewritten as

$$S(x) = \iint_{\Omega-\omega} \frac{1}{\sqrt{2\pi}i} \exp\left[-\left(\frac{x}{\sqrt{2}i}\right)^2\right] d\xi d\eta \tag{10}$$

Comparing Eq. 7, it is easy to find that the two forms are unified when there exists

$$r(z) = \sqrt{2\pi}i \tag{11}$$

When the excavation section scale is much smaller than the burial depth, the calculation results are consistent if both adopt the same assumption of normally distributed curved section settlement troughs. The transformation of i and r can be achieved using Eq. 11 under the premise that the settlement trough widths are equal, whereas the calculation of i widely uses the linear empirical expression can be shown as follows (O'Reilly and New, 1982):

$$i = Kz_0 \tag{12}$$

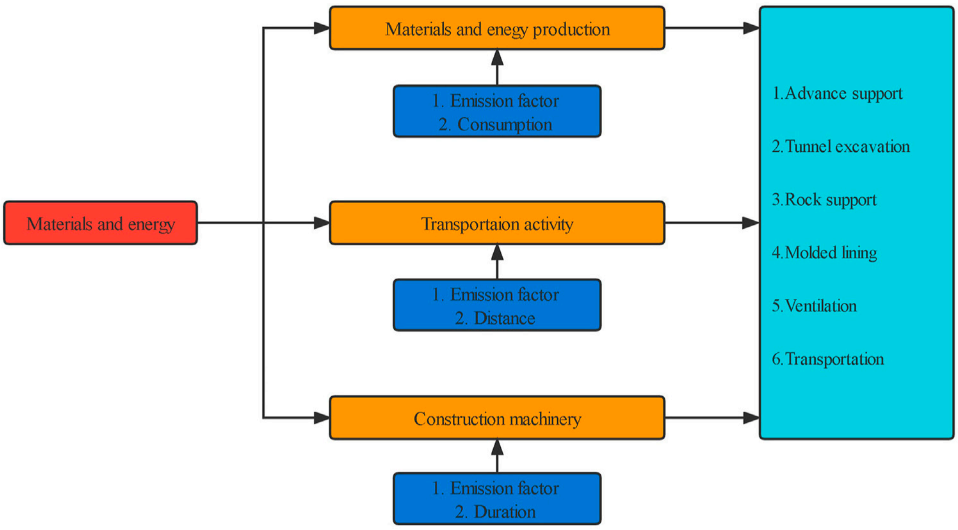

FIGURE 4
Calculation boundary of carbon emission in tunnel construction process.

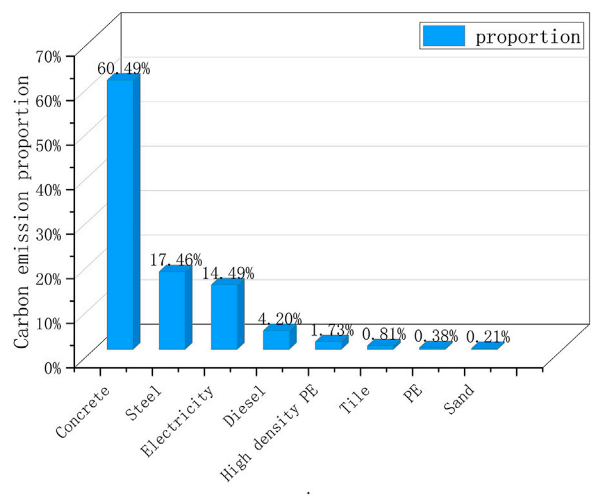

FIGURE 5
Carbon emission proportion of different materials and energy used in tunnel construction.

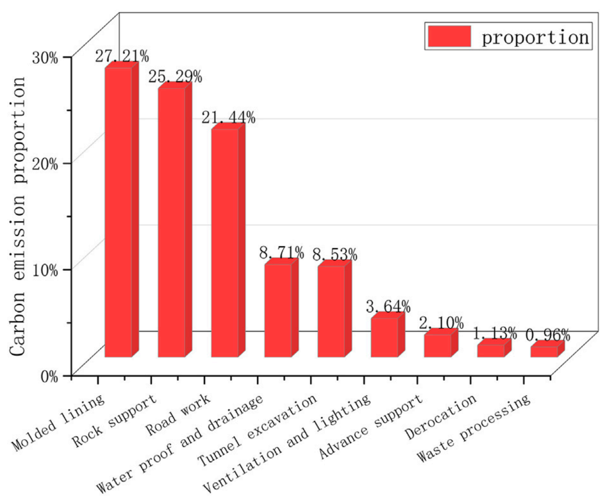

FIGURE 6
Carbon emission proportion in different procedure in tunnel construction.

z_0 is the burial depth of the axis of the underground structure and K is the coefficient of the width of the settlement trough.

When the tunnel burial depth is shallow, the excavation scale is not negligible compared with the burial depth, and when the superposition of Gaussian curves of surface settlement caused by collapsing microunits does not fully comply with the normal distribution, the $\Omega - \omega$ area directly determines the surface settlement pattern, which is generally equivalent to the area of the plastic zone of the section after excavation, which is also in line with the logic that controlling plastic deformation is an effective way to inhibit the expansion of the overall deformation (Wang and Zhang, 1998). In addition, the theoretical expression of the stochastic medium introducing the section convergence radius ΔR can also be considered as the equivalent physical quantity of AV_l in the Peck method equation, which can also be divided into a uniform convergence mode with average ΔR components and a non-uniform convergence mode with different components according to whether the radial convergence is uniform. This also provides an idea for the selection of monitoring indicators to measure surface settlement; when surface deformation cannot be directly and effectively, the development of surface settlement can be indirectly predicted by the radial convergence deformation of the tunnel.

When it is necessary to focus on the influence of different excavation schemes on ground settlement, the observed or simulated value of ground settlement can be selected as the primary indicator, and the maximum plastic zone of the surrounding rock, amount of arch settlement, and amount of free convergence represented by the arch foot convergence as key indicators, as auxiliary reference items for direct calculation results to strengthen the reliability of the demonstration.

Criteria for assessing the stability of support

Rock pressure is the pressure directly acting on the support structure system caused by the deformation of the surrounding rock and is the main source of load for the support system. The deformation pressure is the main and most common form of pressure, which refers to the internal force of the support and the contact stress between the supports caused by the deformation of the surrounding rock. When the buried depth of the tunnel is shallow, it is difficult for the surrounding rock to form a complete pressure arch, and the pressure acting on the structure is approximately linearly distributed according to the buried depth. When the buried depth reaches the depth at which the surrounding rock forms a complete pressure arch, the pressure acting on the tunnel structure only comes from the surrounding rock, which is called deep burial. The lack of a pressure arch and uneven pressure distribution are the fundamental reasons for the design of temporary and permanent support for shallow and ultra-shallow buried tunnels, which is much more difficult than for deep buried tunnels because the support systems at this point not only need to directly share the extra active load, which is offset by the original arch effect in deep buried zones, but also to offset the more significant induced ground settlement than in the deep buried area; therefore, it is necessary to establish an evaluation indicator system for support stability based on relevant theories and existing work for shallow or ultra-shallow buried tunnels.

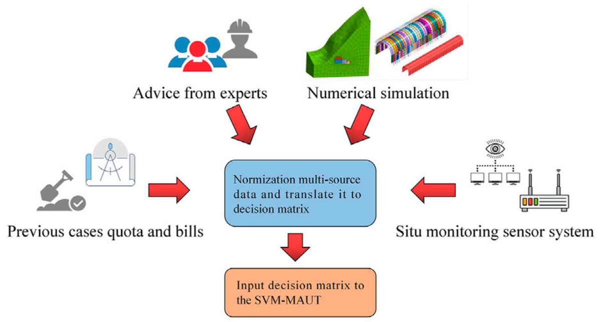

FIGURE 7
The input source of SUM-MAUT model used in the excavation scheme evaluation tasks.

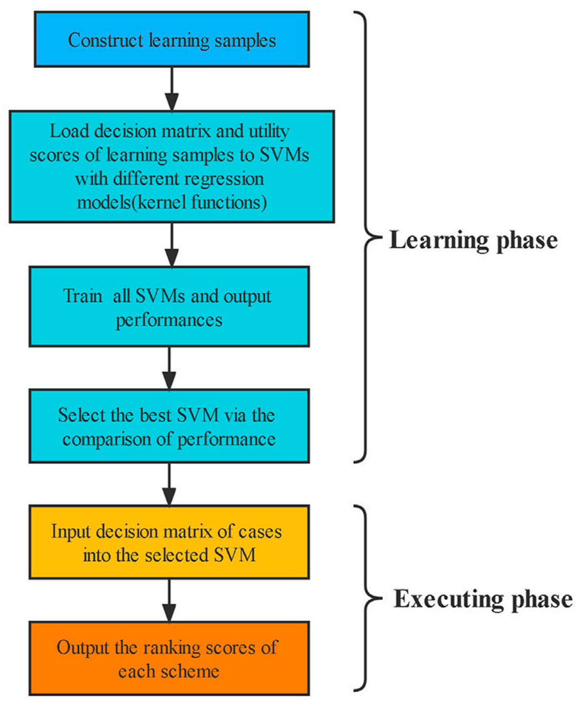

FIGURE 8
Flow of SVM MAUT.

Under the guidance of the New Austrian Tunneling Method (NATM) concept developed on the basis of the continuous medium theory, the elastic resistance of the support plays an important role in limiting the further development of the surrounding rock deformation. Therefore, discussing the coupling effect between the support and the surrounding rock is a reasonable way to make a reasonable selection and ranking of the evaluation indicators involving the stability of the support system. The convergence-confinement method is commonly used for the stability analysis of tunnel rock-support coupling systems (Paraskevopoulou and Diederichs, 2018). The idea is to examine the convergence curves of the rock and support at the same scale and analyze the state when they reach the same value of convergence steady state, and to consider the support and rock as a stable joint system rather than as individual isolated load-bearing elements. In the process of the convergence-confinement method, it is particularly useful to use the surrounding ground reaction curve (GRC), support characteristic curve (SCC), and longitudinal deformation curve (LDP), of which the first two are the curves describing the relationship between stress and displacement of each medium, respectively, and the latter is the curve describing the distance between the section deformation and excavation surface. All three considered the mechanical and geometric properties of different rock masses in different engineering environments during the time scale excavation process. Under the assumption that the deformation of the surrounding rock eventually converges, the GRC will intersect the horizontal coordinate, that is, the radial stress is zero (as shown by the black curve in Figure 3), which means that the surrounding rock can eventually stabilize itself after releasing sufficient deformation, even if no support is provided. However, in the case of shallow buried tunnels, where the strength of the surrounding rock is extremely weak and the self-gravity of the plastic zone is extremely pronounced, the curve will show an upward trend (as shown by the red curve in Figure 3), indicating that the application of support is essential from the point of view of maintaining the tunnel section. In most cases, the purpose of the support system is to limit the development of radial convergence of the surrounding rock by artificially creating a new pressure-deformation state. It can be further seen that the stiffness of the support is designed to cope with the surrounding rock pressure, and the joint GRC-SCC curves show that with the development of convergence deformation, the surrounding rock pressure will be reduced appropriately, and in its place is the question of whether the development of the surrounding rock deformation can meet the design requirements. Therefore, the assessment of the support can be transformed into the assessment of the pressure and deformation state of the surrounding rock support system when it reaches the steady state by relying on the convergence confinement method curves, which correspond to the stress and deformation of the surrounding rock in the process of selecting different excavation methods.

For tunnel structures with secondary lining or composite linings, the scheme assessment of the final state often ignores the initial support and only considers the global support role of the secondary lining, resulting in the calculated values of the surrounding rock pressure acting on the secondary lining being greater than the support pressures of the secondary lining, and the results tend to be conservative (Tang, 2009), thus only through the internal stress of the secondary lining to assess the impact of different methods on the final stability of the

TABLE 1 Comparisons of 7 main machine learning algorithms used in regression tasks.

	Advantage(s)	Disadvantage(s)	Accuracy	Robustness	Sensitivity to missing values
Linear regression	Simple and intuitive	No non-linearity and particularly sensitive to outliers	Modest	Low	High
Polynomial regression	No normalization required; high interpretability	Computational complexity is high	Modest	Relatively high	High
Artificial nerual network	Generalized and non-linear; theoretically fit all pattern recognition problems	Tendency for high variance and overfitting; bad interpretability; gradient disappearance and gradient explosion	High	Modest	Low
Decision tree (CART)	Good interpretability	Easy to over-fit; difficult to adapt to complex structural relationships	Modest	Modest	Low
LASSO regression	Suitable for cases where the feature dimension is much higher than the number of samples	Highly sensitive to noise	High	Relatively low	High
Support vector machine	High generalization ability; maintain good results when feature dimension is larger than the sample size	Too much computation on large sample data sets	High	Relatively high	High
Ridge regression	Suitable for models where features are highly correlated with each other	Because of the nature of regularization, performance is considered inferior to that of LASSO	Modest	Modest	High

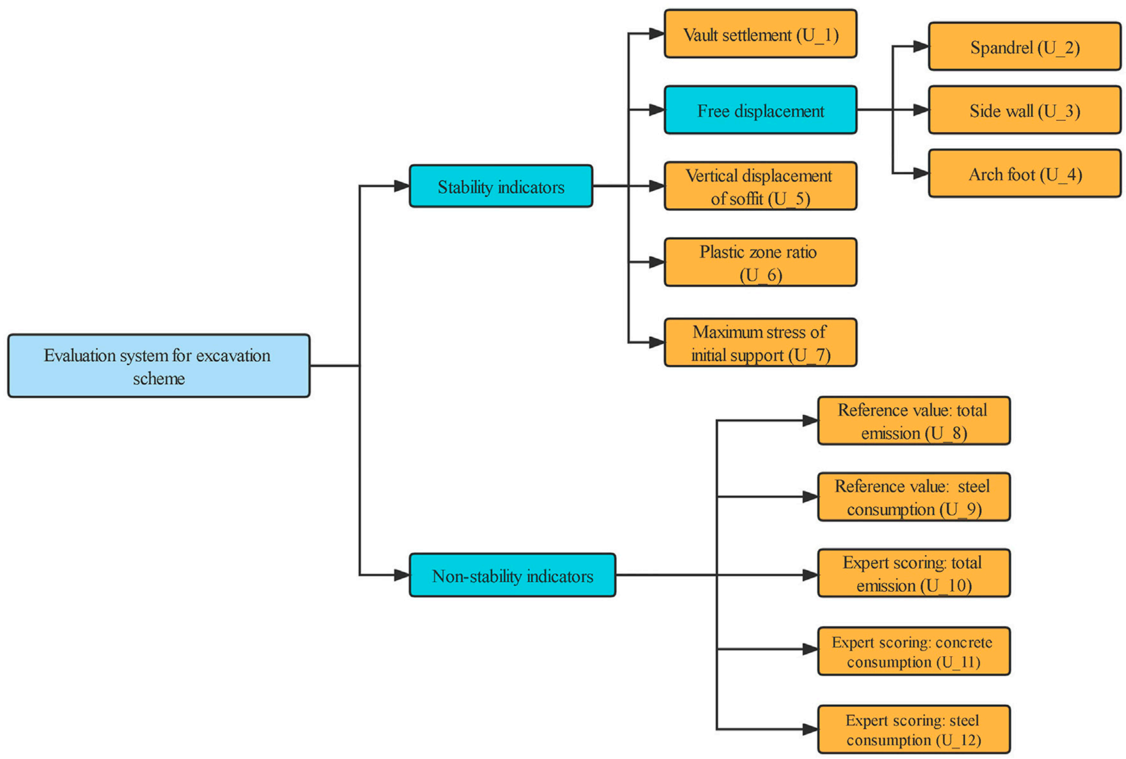

FIGURE 9
Evaluation index system used in this case.

TABLE 2 Learning samples of each indicator and utility scores based on previous engineering case.

U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	E_{uti}
10	6.67	6.67	6.67	10	8.97	7.40	5.65	3.46	6	8	4	0.60
8.69	10	10	10	6.89	6.98	9.16	5.65	10	8	8	6	0.40
8.06	8.33	8.33	8.33	6.38	10	10	10	2.31	6	6	4	0.65
10	10	10	10	10	10	9.71	5.65	5.46	6	8	8	0.40
7.34	7.94	7.94	7.94	6.10	6.54	10	10	5.46	6	6	4	0.60
8.02	9.92	9.92	9.92	9.01	7.78	9.44	2.88	10	6	8	8	0.80
10	10	10	10	10	6	10	10	4.20	10	8	8	0.10
5.40	7.66	5.79	6.14	5	6	9.17	10	10	8	6	6	0.70
3	3.73	3.36	1.32	2.35	4	4.56	10	6.62	6	6	4	0.95

support is feasible; however, to assess the stability of the support during the current method, it is inevitably necessary to discuss the internal stress and deformation before and after the closure of the support.

In the support and lining system, shotcrete, cast-in-place concrete, and steel arches are continuous units that fit well to the tunnel section, whereas anchor rods are relatively individual units that are discrete in the joint support system. The main indicator factor for measuring the stability of anchor rods is the axial tensile force, which can be measured by numerical simulation or sensors such as anchor rod axial force meters in the field and laboratory (Li et al., 2018), Based on this, the anchor rod stress diagram of the test section can be generated to determine whether the anchor rods as significant support members maintain a high degree of cooperation with the mechanical process of the rest of the support system under the current excavation scheme, thus achieving a common support effect.

Carbon emission indicator selection and quantification

Quantification of carbon emission under life cycle theory

The process of quantifying carbon emissions is an effective combination of the currently existing carbon footprint tracing and carbon emission calculation processes; the former aims to clarify the latter calculation boundary, and the latter accumulates the carbon emission effects of each node marked by the former tracing based on available information (e.g., bill of quantities); however, there are two main problems in assessing the differences in carbon generation between each excavation scheme: 1) Most scheme evaluation stages do not have clear and detailed lists of the corresponding projects, so it is impossible to carry out accurate carbon emission calculation; 2) The calculated carbon generation under different calculation boundaries is different, and different standards may even produce different horizontal comparison results for alternative excavation schemes. For the first problem, the reference values can be obtained by investigating the calculation results of existing projects and adding some key indicators for reference correction; thus, the problem can be transformed into statistics of carbon emission data of different excavation methods and determination of the remaining evaluation indicators. For the latter problem, it is necessary to determine a broad-spectrum estimation model under a strong envelope framework to adapt to the application of engineering cases with actual situation changes.

TABLE 3 Reference values of average concrete and steel consumption per linear meter for different excavation schemes.

	Type	Concrete (m^3)	Steel (Kg)
Excavation scheme	CD	10.19	692.83
	CRD	24.27	391.55
	Both side drifts	16.07	831.78
	Two benches	5.56	345.71
	Three benches	4.32	140.83
	Core soil	3.72	123.11

Carbon emissions in the strict definition are the general terms for greenhouse gases (methane, nitrogen oxides, sulfur hexafluoride, HFCs, etc., including carbon dioxide) produced in the engineering process, all of which are converted into carbon dioxide equivalent values $CO2_{eq}$ uniformly according to their contribution to the greenhouse effect, which is the carbon emissions in a broad sense.

In the tunnel construction process, the most direct source of carbon emissions is the carbon oxides and nitrogen oxides generated by the operation of the fuel machinery, excluding the carbon generated by the energy consumption of the machinery. The emissions generated by the production and transportation of various engineering materials and energy sources have a considerable impact on the environment, even in terms of emissions far beyond the direct application phase

TABLE 4 Scoring results of each excavation scheme in this case.

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	E_{uti}
A_1	8.99	8.73	7.40	9.89	10	8.08	10	5.65	2.30	6	6	6	0.5552
A_2	7.96	7.73	9.12	8.37	9.82	8.14	8.09	10	4.20	7	8	6	0.4564
A_3	7.68	7.82	10	8.18	9.81	10	7.97	10	10	6	8	7	**0.5881**
A_4	10	10	7.42	10	9.15	10	6.32	10	6.62	8	9	8	0.3099

(Chen, 2017); Furthermore, when examining the tunnel construction process, the excavation and support (including over-support and rock support) and lining construction will involve large amounts of concrete and steel components (anchors, steel arches, etc.,), and the input of consumables in subsequent drainage prevention works, roadbed pavement works, and ventilation and lighting works is also a non-negligible factor, but only for the excavation scheme selection phase of tunnel construction, its consideration needs not be extended to the stage after the main body of the tunnel is formed, so the calculation boundary is shown in Figure 4.

Using this calculation boundary as the guide, a preliminary quantification of the key nodes of carbon emissions for the entire process of tunnel construction is discussed in conjunction with existing engineering cases (Guo et al., 2019): the tunnel in this case is located in Sichuan Province, China, which is a double-bore highway tunnel with four lanes, combining the designs and survey in the pre-construction stage mentioned in the corresponding literature, other organizational process assets and information provided by the upstream supply chain, as well as combining the IPCC, CLCD database, Chinese national official data, etc., the process of production and transportation of engineering consumables and energy transportation are converted into carbon emission equivalents, and the emissions of various types of energy and materials (Guo et al., 2020) are obtained, based on which the contribution of different processes and different materials and energy sources to the carbon emissions of the whole process are as Figures 5, 6 show.

As can be seen from the figures, the initial support work and the secondary lining (i.e., molded lining) work contribute the most carbon emissions in the construction implementation (27.53% and 25.59%). From the perspective of energy and materials, concrete accounts for 60.49% of global emissions and steel accounts for 17.46% of global emissions, which shows that carbon emissions from support work is an absolutely non-negligible factor under the guidance of the life cycle theory, which provides guidance for the addition of carbon emission assessment indicators. For example, although the single-side drift method and both side drift methods are both benching excavation methods with side drift (s), their support workloads are significantly different, so it is obvious that the carbon emission values of the two methods are not equivalent under the same objective conditions. Therefore, it is necessary to introduce the support construction workload as an indicator to participate in the measurement of carbon emission indicators and to make a reference comparison table according to the bill of quantities of the existing works for the comparison of subsequent methods.

As the mechanization level of tunnel drilling and blasting construction processes has been increasing in recent decades, the contribution of electricity to carbon emissions in terms of energy consumption is as high as 17.46%, which is much higher than that of diesel (4.60%). The calculation of carbon emissions caused by mechanization can give priority to electricity consumption to be considered, so electricity consumption can be used as a supplementary indicator to evaluate the carbon emissions for different schemes.

The mean values of carbon emissions under different excavation scheme series have been presented in the relevant literature (Guo et al., 2020), based on which other data sources (Yang, 2003; Zheng, 2016; Chen et al., 2020) were incorporated to derive more comprehensive statistics on the scale as shown in Table 1.

On this basis, further research is conducted to summarize the reference values of the average amount of concrete and steel consumption per linear meter for more specific common excavation methods such as the center diagram method, center cross diagram method, and both-side drift methods. The results are as Table 2 shows.

TABLE 5 Comparison of the effectiveness of training results under five regression models.

Regression	RMSE	R-squared	MSE	MAE
Linear	0.19561	0.50	0.038264	0.15569
Quadratic	0.183	0.57	0.033491	0.15149
Cubic	0.18272	0.57	0.033385	0.14817
Fine Gauss	0.28073	−0.02	0.07881	0.22409
Coarse Gauss	0.25611	0.15	0.065592	0.20738

TABLE 6 Numerical simulation results of tunnel section in alternative excavation scheme.

Item	Bench (A_1)	CD (A_2)	CRD (A_3)	Both side drifts (A_4)
Vault settlement (cm)	0.695	0.615	0.594	0.773
Spandrel displacement (cm)	1.226	1.086	1.099	1.405
Sidewall displacement (cm)	0.745	0.689	0.747	1.098
Arch foot displacement (cm)	0.637	0.539	0.527	0.998
Soffit displacement (cm)	0.450	0.315	0.304	0.399
Maximum stress of support (Mpa)	3.309	2.543	2.254	2.345
Ratio of plastic zone	39.2%	39.5%	48.5%	48.5%

The above tables provide a reference basis for the decision-making stage of excavation methods in the absence of a detailed bill of quantities, and the integration of expert scoring to assess the gap between each excavation method on each project is also needed, because the same excavation method in the application process inevitably performs differently for various engineering conditions; the introduction of expert scoring is a way to inhibit the emergence of this unfavorable situation, which will be discussed further in subsequent sections.

Comprehensive evaluation indicator system for carbon emission

According to the results of the above discussion, in the absence of the bill of quantities, the following carbon emission evaluation indicators proposed for different tunnel excavation schemes are listed: average value of total emissions in previous cases, reference value of concrete consumption in previous cases, reference value of steel consumption in previous cases, expert scoring value of total emissions in the current method, expert scoring value of concrete consumption in the current method, and expert scoring value of steel consumption in the current method.

When the quantification of all alternative excavation schemes is completed and the bill of quantities is clear, the evaluation indicators are the value of total emissions of each method, the reference value of concrete consumption in previous cases, the reference value of steel consumption in previous cases, the consumption of concrete in the current method, the consumption of steel in the current method, and the carbon emission equivalent of electricity in the current method.

TABLE 7 Summary of the average carbon emission equivalent values for different excavation schemes (series).

	Type	Sample value	Mean of CO_2eq	Standard deviation
Excavation scheme (Series)	Full face	6	6.74	1.19
	Bench	15	15.67	8.01
	Core soil	3	7.99	0.69
	Drift(s)	31	27.73	11.06

TABLE 8 Linguistic terms used in proposed model.

Value	Definition
1	Extremely small
3	Relatively small
5	Normal
7	Relatively large
9	Extremely large
2,4,6,8	Compromise interpolation

Full comprehensive evaluation index system with carbon emission indicators

Summarizing the previous, all indicators in attribute layer are now unified into a parallel relationship to realize that different attributes can be flexibly combined to adapt to different realistic requirements, and the recommended evaluation indicator systems are given as follows.

Evaluation index system with stability of surrounding rock as control factor

The indicator variables that must be included in the evaluation indicator system are vault settlement (monitoring and numerical simulation), at least one free convergence value represented by the arch foot (monitoring and numerical simulation), maximum principal stress (numerical simulation), and area (ratio) of the plastic zone (numerical simulation).

The system indicator variables selected according to the actual engineering cases are soffit deformation (monitoring, numerical simulation), vertical displacement associated with the free convergence represented by the arch foot (monitoring and numerical simulation), displacement at the bench intersection (monitoring, numerical simulation), and convergence displacement of the palm face (monitoring and numerical simulation).

Evaluation index system with ground settlement as control factor

The variables that must be included in the evaluation indicator system are the maximum surface settlement (monitoring, numerical simulation), vault settlement (monitoring, numerical simulation), at least one pair of vertical displacements represented by the arch foot (monitoring, numerical simulation), and plastic zone area (ratio) (numerical simulation).

The system variables selected according to the actual engineering cases are soffit deformation (monitoring, numerical simulation) and displacement at bench intersection (monitoring and numerical simulation).

Evaluation index system with support stability as control factor

The variables that must be included in the evaluation indicator system are the deformation of the surrounding rock at the vault (monitoring and numerical simulation), at least one pair of free convergence values of the surrounding rock represented by the foot arch (monitoring and numerical simulation), the area (ratio) of the plastic zone (numerical simulation), the maximum bending moment/tension of the closed initial support (numerical simulation), and the final lining stress (numerical simulation).

Based on the actual engineering situation, the following system variables were selected: elevation deformation of arch foot (monitoring, numerical simulation), vertical displacement associated with support prograde convergence represented by arch foot (monitoring and numerical simulation), surrounding rock displacement at bench intersection (monitoring, numerical simulation), anchor tension (monitoring, numerical simulation), maximum bending moment/tension of steel arch (numerical simulation), and other inter-media forces (monitoring and numerical simulation).

Multi-objective portfolio evaluation index system

Scheme decisions in practical cases may need to take into account a variety of stability factors at the same time, so it is necessary to re-add or organize the evaluation indicator system, but must be included in the evaluation indicator system are: vault settlement (monitoring, numerical simulation), at least a pair of free convergence values (monitoring, numerical simulation), plastic zone area (ratio) (numerical simulation), at least one medium of stress or internal force distribution (monitoring, numerical simulation).

Additional measurement and evaluation items should be added according to the other requirements in the design plan.

Intelligent decision-making method

Defects of traditional evaluation methods

Among the available comprehensive evaluation models, the most commonly used to select excavation schemes in tunnel engineering are the analytic hierarchy process (AHP) (Li et al., 2019), TOPSIS, fuzzy comprehensive evaluation, and other evaluation methods with weight coefficients.

Using the optimal excavation scheme selection of Xiaozhai tunnel using the AHP method (Zheng, 2016) as an example, it clarifies the target layer, program layer, and criterion layer objects after arguing the actual aspects of the project, establishes the judgment analysis matrix on this basis, transforms the priorities of all qualitative indicators into a quantitative matrix in the process of pairwise comparison with the help of linguist terms (Table 3), performs a consistency test, generates the sorting results under each criterion, and obtains the final selection results. Although there are only five evaluation criteria and four evaluation schemes, the computational process to be followed is slightly tedious, and the four judgment analysis matrices need to be tested sequentially in the consistency test. Once any direction (criterion or alternative program) is extended or both are extended at the same time, the computational expense increases significantly and the matrix consistency is more difficult to guarantee strictly; meanwhile, the process cannot be simplified.

Although the TOPSIS method has fewer subjective factors than the AHP, the entropy weight method, which is the main basis for the calculation of weight coefficients, requires sufficient experimental data to support, which increases the difficulty of practical application. In the study of the optimal excavation method for the southern limb of the access line of Tiantongyuan Station of Beijing Metro Line 17 (Wu et al., 2020), engineers relied on *in situ* section testing and set up 16 orthogonal tests to derive four evaluation indicator weights, which caused a certain amount of time and resource consumption.

To address the shortcomings of the above evaluation methods, the following improvement requirements were proposed and used as a basis to explore a comprehensive evaluation method based on machine learning techniques:

1) It can directly, conveniently and effectively combine experts' engineering experience with numerical simulation and field measurement results;

2) It has relatively fixed evaluation pattern without tedious weight computation;
3) It has good scalability;
4) It has good programmability and executability in computing equipment.

Initial idea is to turn the evaluation problem into the quantifiable regression problem. There are many existing machine learning algorithms available for regression tasks, but different mechanisms imply differences in the applicability of the algorithms to specific problems. We conducted comparisons of the available algorithms, and the ensemble learning algorithms were not considered due to performance overflow. Seven mainstream algorithms were finally selected, and the results of the comparison are as Table 4 shows.

Considering that the proposed evaluation system is a mixture of independent attributes (stable and non-stable factors) and correlated attributes (e.g., surface settlement and convergences), it is clear that both LASSO and ridge regression algorithms are not applicable to the evaluation task proposed in this paper. Only the CART algorithm among decision tree algorithms is competent for the regression task, and the pruning in the process implies particularly tedious computation, especially when the hierarchical relationships are complex (i.e., when there are many decision attributes). Artificial neural network method has been applied in existing study (Ghasemi and Asgharizadeh, 2014) and exposed the problem of fluctuating prediction results due to overfitting, so there is still a need for enhancement. For linear regression and polynomial regression, both are prone to the extremes of overfitting and underfitting, and are too sensitive to noisy samples.

Although the support vector machine method has some drawbacks, such as low tolerance for missing values and too much computation on large sample data sets, it is worth noting that based on the evaluation index system, the sample size we build cannot be too high and all the missing key indicators should be re-simulated to ensure the quality of the index data, so the support vector machine is worth being considered as the computational module.

Support vector machine evaluation method with utility function

The excavation scheme selection problem belongs to the multi attribution decision making (MADM) problem, which can be solved by coupling the support vector machine with the utility function approach (Wang et al., 2006), This refers to the use of a multi-attribute utility function (MAUT) by constructing a mapping of performance in each attribute to the overall utility value of each scheme, and then ranking the utility values of each scheme to determine the priorities for each alternative scheme.

In the previous decision methods, attribute weights reflect the degree of difference between attributes and the importance of the attributes to the decision maker. However, the proposed method only needs to learn the expert's decision pattern by learning the scoring values under each attribute of the alternative excavation scheme in previous projects and the utility values calibrated with the actual project, without the direct calculation of each attribute weight coefficient.

Support vector machine is a powerful machine learning algorithm, which is based on decision boundary theory and replicates the mapping relationship between samples and labels. As one of supervised learning models, there are two phases in SVM regression process: learning phase and regression phase. In the learning phase, input training dataset is used to train the SVM model, in which a decision boundary is formed from an optimum separating hyperplane that best fits all data samples. Data samples that lie on the decision boundary are namely Support Vectors (SVs), which are defined in the learning phase and are then used for the regression tasks.

The following paper focuses on its combination with multi-attribute utility functions (MAUT) and briefly describes how this SVM-MAUT method can be used in case applications for alternative evaluation. The flow of SVM-MAUT model can be shown as Figures 7, 8, Tables 5, 6 show.

For the scheme evaluation and selection summarized in the existing works, the scores of each attribute indicator are standardized by a decimal system, and the indicators that need to be scored by experts are assigned a decimal system following a linguist terms table. The continuous-valued indicators from tests or simulations are decimalized on a uniform scale; the final utility is specified as a continuous decimal between 0 and 1; this transformation and quantification criterion is common to all training, validation, and test set data.

In the process of previous scheme selection, especially in the description of the plastic zone, most of the literature did not use detailed data to express, but used vague linguist descriptions such as "large" and "small" to describe, for such subjective factors that lead to the uncertainty of the indicators, it is necessary to introduce the linguist terms table (Table 3) that can maintain the accuracy and is compatible with the system to correct it; for cases where too much natural linguist scales is used to describe the indicator, it cannot be used as learning samples due to the model requirement of accuracy and robustness.

The main advantages of this method are as follows:

1) It is not necessary to know which schemes were chosen by the experts in which comparison tasks; only the combination of attribute values and total utility values of a certain scale can be learned to capture the expert's decision pattern and generate memory of the expert's decision orientation with the corresponding pattern.
2) This method bypasses the previous problems of converting qualitative concepts to quantitative representations (i.e., the affiliation function problem) or unifying the scales in the process of fusing continuous and discrete values.

3) The attributes corresponding to the project set and the evaluation index system can theoretically be expanded without restriction within the acceptable range of computational expense, and the size of the consistency matrix of AHP, for example, is limited to 15, which cannot meet the requirements of scheme evaluation when the type of indicator is beyond 15.

Case application and discussion

In this study, the excavation scheme selection for a shallow buried subway tunnel under the existing highway at Xiamaixi Station of Guiyang Metro Line No. 1 was considered as an engineering case (Song et al., 2019). The total length of the tunnel is 528 m, and the line is designed as a single two-lane structure, with a total of 110 m of tunnel under the highway embankment and culvert exit.

The geological conditions of the shallow buried tunnel under the highway are poor, and the geotechnical investigation report shows that the geological components of the underpass section are mainly shale and the quaternary soil layer, the rock fragmentation degree belongs to grade V surrounding rock, the highway road surface is 23 m from the vault of the underpass tunnel, and the highway should be used during tunnel construction. Therefore, the tunnel section in this case is a classic shallow buried tunnel with various challenges in terms of engineering stability. The combination of vault settlement, free displacement of the spandrel, side wall, and arch foot, vertical displacement of the soffit, plastic zone ratio, and maximum stress of the initial support were selected as the stability factor part of the index system to evaluate the alternative excavation schemes in this case. The alternative excavation schemes included the up and down bench method (A_1), center diagram (CD) method (A_2), center cross diagram (CRD) method (A_3), and both-side drift method (A_4).

Using the 3D finite element calculation models built on MidasGTS/NX, the optimal excavation scheme was obtained by simulating four different excavation schemes considering the three-dimensional effect during the tunnel excavation process and comparing the indicators of displacement field changes and stress conditions under different excavation schemes. In view of the complexity of the geological conditions, the model was simplified by treating both the tunnel envelope and soil as anisotropic, and the yield criterion was adopted from the Mohr-Column criterion. In the actual construction, the anchor rods were made of steel, and the initial support and secondary lining were mainly reinforced arch and concrete; therefore, their yield criterion was linear elasticity, and the 2D unit simulation was used. The equivalent modulus of elasticity of the initial support was calculated using the aforementioned discounting strategy and simulation method.

To avoid the aforementioned three-dimensional effects, the middle section of the tunnel (X = 85.5 m) was selected for the analysis and comparison.

In the Midas simulation, the steps of the bench method were as follows: the upper bench was constructed first; the length of the upper bench was 20 m per cycle; the lower bench was constructed; and the distance between the upper and lower steps was 20 m. The construction steps of the CD method were as follows: excavating the left side of the tunnel first, then excavating the right side of the tunnel; the CRD method construction steps were as follows: the left side of the tunnel section and the right side of the tunnel were excavated alternately; both side wall drifts method was similar to the CD method; the steps were as follows: first, the left side of the tunnel was excavated, the intermediate core soil was preserved during this period, and then the middle section of the tunnel was excavated. Except for the bench method, each cycle advance was 3 m in length for all three remaining schemes. The results of the simulation are as follows:

Considering that previous cases of excavation scheme evaluation and selection were carried out without bills of quantities, the non-stability factors of the evaluation index system consisted of the reference value of total emissions and steel consumption in previous cases, and the total emissions and consumption of concrete and steel in the current method judged by experts.

According to the reference comparison table based on the bill of quantities of the existing works, there are obvious differences between bench methods and side drift methods (CD, CRD, and both-side wall drift wall method) in mean values of carbon emissions, while the more detailed gap between the three alternative schemes has not been presented due to the limitation of statistical results; therefore, we scored all the three methods in the side drift method series in values of 10 in the comparison sorting process, while the values of the bench method have been scored as 5.65 after decimal normalization; the scores of the four schemes in U_8 were determined. The reference values of concrete consumption in the cases mentioned above are more explicated, and the corresponding table offers specific values for each scheme. According to the decimal normalization process, the values of U_9 in the four schemes can be scored as 2.30, 10, 4.20, and 6.62.

The expert scoring indicators are U_{10}, U_{11} and U_{12}, in which the experts involved in the project thought that the emission gap between the CD and CRD excavation scheme would not be the same as the regular logic shown in previous cases: the tunnel length in this case is too short to be measured by the linear meter, while the steel kits used to support the medium section of the vault should be preproduced, and the indirect emission caused by them is higher than the total emission of used concrete and steels in the CRD excavation scheme; therefore, the values of expert scoring for total emissions in the four schemes are different from the distribution of previous reference results. When it comes to the consumption of concrete and steel, experts held the same opinion with previous cases, the both side drift method would cost the most materials in the same condition, so, this scheme obtained the highest values in both indicators (U_{11} and U_{12}), all the scores can be shown in Table 7.

Evaluating by proposed SVM-MAUT

As Figure 9 shows, there are 12 types of indicators in the evaluation index system designed to evaluate this case, based on which learning samples have been constructed (Zhang, 2012; Mou et al., 2017), and all the samples should contain complete information for each indicator. In other words, the missing value should not appear in this process because of the sensitivity to missing values in support vector machine algorithm, which is a difficult line for the determination of learning samples. To address this requirement, some supplementary numerical simulations were executed, and the description of the plastic zone was translated according to the proposed linguistic terms. All utility scores were determined by experts. The samples are as follows:

In this study, five regression models (i.e., kernel functions) used in the support vector process were considered, and the model with the best performance (RMSE validation) was determined as the final regression model used in subsequent studies. The performance measurements for each regression model are as Table 7 shows.

The SVM with the cubic kernel function was determined because of its idealist performance in RMSE. Then, by inputting all the normalized data for indicators of the four alternative schemes to the pretraining model, the utility ranking scores can be calculated as Table 8 shows:

It is easy to observe that the CRD method has the highest score, which indicates that the CRD method is the optimal solution for carbon emission control under the premise of maintaining safety stability, while the bench method cannot be the optimal solution because it cannot provide sufficient capacity to maintain stability; however, the both-side wall drift method has the lowest score after fully considering the carbon emission factor, which indicates that the scoring model effectively integrates the elements based on the existing engineering samples and expert experience, and effectively realizes the concept of safety factors as the dominant factor proposed in this paper.

Evaluating by TOPSIS

The basic process of TOPSIS is to first normalize the original data matrix to obtain the normalized matrix to eliminate the influence of each index scale, and find the optimal solution and the worst solution among the finite solutions, and then calculate the distance between each evaluation object and the optimal solution and the worst solution respectively to obtain the relative proximity between each evaluation object and the optimal solution, which is used as the basis for evaluating whether the solution is ideal or not.

Previous indicator combination (U_1–U_{12}) and alternative scheme set (A_1–A_4) were still used, while the learning samples were not be used in TOPSIS, it is obvious that all the indicators are cost index, so the input data needs to be transformed by the transformation equation before normalization:

$$x_i^{\sim} = max - x_i \tag{13}$$

Normalization process follows equations as below:

$$z_{ij} = \frac{x_{ij}^{\sim}}{\sqrt{\sum_{i=1}^{4} x_{ij}^{\sim 2}}} \tag{14}$$

Obviously, the normalized matrix Z is with size of 12×4, definitions of idealist objects Z_+ and worst objects Z_- follow below equations:

$$\begin{aligned} Z_+ &= (Z_{1+}, Z_{2+}, \ldots, Z_{12+}) \\ &= \left(max\ \{z_{11}, \ldots, z_{14}\}, \ldots, max\ \{z_{12,1}, \ \ldots, z_{12,4}\}\right) \end{aligned} \tag{15}$$

$$\begin{aligned} Z_- &= (Z_{1-}, Z_{2-}, \ldots, Z_{12-}) \\ &= \left(min\ \{z_{11}, \ \ldots, z_{14}\}, \ldots, min\ \{z_{12,1}, \ \ldots, z_{12,4}\}\right) \end{aligned} \tag{16}$$

The distances between each object (each scheme in this case) and idealist or worst objects can be determined as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{12} \left(Z_{+j} - z_{ij}\right)^2} \tag{17}$$

$$D_i^- = \sqrt{\sum_{j=1}^{12} \left(Z_{-j} - z_{ij}\right)^2} \tag{18}$$

The score of objects (schemes) can be defined as follows:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{19}$$

Corresponding indicator samples have been selected from Tables 3, 8. The scores of 4 alternative schemes are: 0.3248 (A_1), 0.2990 (A_2), 0.2592 (A_3), 0.1171 (A_4), the bench method has been obtained the highest scores, which is a serious violation of the principle of selecting schemes with safety as the dominant consideration, because in the numerical simulation, the bench method has the highest value of each displacement. It is obviously that original TOPSIS method cannot offer reasonable scoring results for the alternative schemes in this case.

Conclusion

This paper attempts to combine several theoretical approaches with realistic scenarios, discusses the association between indicators that can be directly observed, and indicators such as mechanical laws that cannot be directly observed. Finally, we summarize and select several collections of evaluation indicators with different orientations based on priority ranking, which provide widely applicable and clear guidance for the selection of stability criteria in excavation scheme evaluation.

For the scheme selection process using numerical simulation analysis as the main data source, this study points out a detailed requirement for the specific orientation of the measurement items and the distribution of measurement points based on relevant theories. For the calculation model using the simplified yield criterion (i.e., the constitutive models without considering the weakening of material properties), the mechanical parameters based on the distribution law of the plastic zone should be discounted and corrected under the premise of accuracy requirements, so as to avoid the error of comparison results caused by the over-simplification of the model. At the same time, it is clearly pointed out that the plastic zone also measures the degree of excavation disturbance of the current excavation method.

Based on the premise of stability indicators, this study also proposes a corresponding method for measuring and evaluating the degree of carbon emissions of different excavation schemes. In view of the objective reality that the engineering inventory is generally lacking in the feasibility evaluation stage, this study takes the carbon emission calculation boundary guided by the life cycle theory as the guide, fully considers and uses a combination of previous engineering data and expert experience, and uses the advantages of each to eliminate the uncertainty of other methods. Thus, the credibility of the results of considering the carbon emission difference of different schemes is further enhanced.

In addition, this paper critically discusses the traditional methods of comprehensive evaluation and ranking based on weight coefficients and points out the problems of cumbersome procedures and large workloads in the calculation of weight coefficients in this series of methods. The scoring method is called the support vector machine-multi attribute utility function method, which combines the measured data, expert scores, simulation results, and previous engineering data in the same computational model and greatly improves the executability of the multi-attribute evaluation by using the superiority of machine learning algorithms in pattern capturing and pattern reproduction. The optimal scheme ranking in the selected case was calculated after integrating the new objectives, achieving effective unification of carbon emission control and construction safety requirements in the scheme selection.

In order to demonstrate the feasibility of the proposed evaluation method, the paper combines the selected engineering cases and compares it with the TOPSIS method at the end, and the comparison results show that the proposed evaluation method is more reliable than the ranking results calculated by the TOPSIS method.

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

ZX contributed to conception and design of the study, wrote the main body of the manuscript. JM and YH revised sections of the manuscript and format. GC and DW proposed some supplementary and DW is as the funding represent to funded the research. 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.

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Impact of climate change shocks on economic growth: A new insight from non-linear analysis

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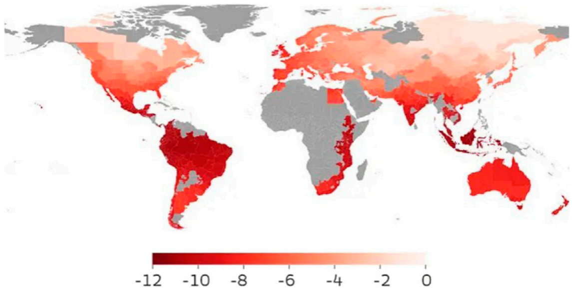
Despite the fact that Pakistan's contribution to GHG emissions is low (0.8%) when compared to other countries but it is one of the hardest hit by climate change. The present study is an attempt to identify the impact of climate change on economic growth. The non-linear autoregressive distributional lag (NARDL) technique is used to estimate the asymmetric effect of climate change on the economic growth of Pakistan. Annual data covering the years 1980–2021 are used for empirical analysis. It is noteworthy to reiterate that CO2 emissions and mean temperature pose asymmetrical results concerning economic growth, both in the long-run and short-run. CO2_POS and CO2_NEG have a negative impact on economic growth, whereas MEANT_POS has a positive impact on economic growth and MEANT_NEG has a negative impact. Precipitation has a positive and significant long-term influence on economic growth. Research findings indicate that comprehensive mitigation policies at the nationwide and worldwide levels are required to limit human-caused climate change in Pakistan. At national level, tree planting projects and safeguard greenery at all costs while at international level, policies needed for adoption of mitigation strategies to control climate change.

KEYWORDS
economic growth, CO2 emissions, asymmetries, NARDL, Pakistan

1 Introduction

Climate change is widely acknowledged as having major consequences for water supplies, agricultural growth, ecology, the health of humans and animals, forestry systems, and socioeconomic sectors (Nordhaus, 1991; Stern, 2006; Tol, 2008). Climate change is predicted to have a greater impact on emerging and impoverished countries than on affluent countries (Gemenne et al., 2014). Climate anomalies are becoming the norm as human-caused climate change exacerbates natural catastrophes worldwide, with the poor bearing the brunt of the repercussions despite being the major cause (Nordhaus, 1991; Stern, 2006). The industrial discharge of Green House Gases (GHGs) grew rapidly after Industrialization. GHGs have a strong warming propensity and a lengthy lifespan (decades to centuries) which can contribute to global warming (Ma et al., 2021; Syed et al., 2022).

The accumulation of GHSs will undoubtedly contribute to global warming (IPCC, 2007a). It should be realised that the climate is not a continuous, unchanging reality even when left alone (Weiss and Bradley, 2001). Carbon dioxide (CO2) accounted for around three-quarters of total GHG emissions in 2018 (World Bank, 2021). As a result, such high levels of CO2 emissions are frequently cited as a primary driver of global warming, and lowering CO2 emissions is typically seen as the most pressing issue for global economies (Liu and Wang, 2022; Murshed et al., 2022). Globally, the researchers discovered that each additional 1°C of day-to-day temperature fluctuation was associated with a 5% reduction in regional economic growth rate in any given year. Even at the regional level, where yearly rates might vary by 16 percentage points each year, this is a significant shift. Forecasts show that if effective CO2 emission reduction measures are not implemented, the global temperature would rise by 3–4 degrees Celsius over pre-industrial levels (NOAA, 2017; Kurramovich et al., 2022). The following map shows how big swings in day-to-day temperature hit economic growth. This map shows the percentage point change in economic growth rates for each extra $1C^0$ of day-to-day temperature variability in any year.



Source: Nature Climate Change/Maximilian Kotz.

The climate change argument arises from a succession of warnings from scientists and others, all of which indicate that human-caused climate change is an impending threat to civilization (Stern 2006; IPCC 2007a). Millions of people may face health consequences, crop production in the low latitudes may decline, water supplies may dwindle, precipitation in arid regions may decrease, extreme events may increase exponentially, and 20%–30% of species may face extinction (Stern, 2006; IPCC, 2007b). Worse, catastrophic disasters such as the collapse of the polar ice sheets might cause major storm surge, flooding hundreds of millions of individuals (Dasgupta et al., 2009). If GHSs are not dramatically cut today, economic development and well-being may suffer (Stern, 2006).

Climate change economic research has long shown that the market economy of agriculture, coastal resources, energy, forestry, tourism, and water is vulnerable to climate change (Pearce et al., 1996). Agriculture and forestry account for a larger share of the economies of developing countries in general. They are also more likely to occur in lower altitudes, in which the consequences on these industries would be more significant. These latitudes are too hot, so profitable agricultural activities are usually difficult, and it is alarming that any further increase in warming will lower production levels even further. Low latitude countries may bear up to 80% of the consequences of climate change (Mendelsohn et al., 2006).

To improve social welfare, sustainable economic growth and development are required. It implies that environmental sustainability should be safeguarded rather than economic progress occurring at the price of environmental damage. It has been emphasized that environmental deterioration is a difficult issue in the process of economic growth. Because environmental deterioration has a direct influence on people's living standards and the operation of the economy. According to empirical studies, lower levels of development are related to climatic conditions that impact economic production (Burke et al., 2015; Kalkuhl and Wenz, 2020). Reduced or even stagnated economic development would be a huge problem, especially for developing countries. It may, however, have distributional consequences in wealthy countries by disproportionately harming poorer regions within nations or more vulnerable sectors of populations (Hirabayashi et al., 2013; Prudhomme et al., 2014).

In the literature, there are various plausible methods for climate change to affect economic growth. Climate change's negative impact on economic growth is supported by both theoretical and empirical evidence. For starters, environmental deterioration caused by attrition, inundation, drought, the extinction of rare taxa, and mortality caused by extreme weather all have long-term ramifications for economic growth. Second, the means necessary to mitigate the effects of climate change would constrain investing in both financial and physical infrastructure, R&D, and intellectual capital, slowing development (Pindyck, 2011; Ali, 2012). The relationship might theoretically be formed using macroeconomic and microeconomic characteristics. Macroeconomic consequences include the impacts on agricultural production and the country's economic propensity to develop (for example, through changing investing or institutions that encourage economic output development) (Dell et al., 2012). The interaction between the microeconomic analysis component and numerous variables like physical and mental productivity levels, conflicts, and well-being may all have an impact on the economy (Gallup et al., 1999).

1.1 Climate- economic growth nexus in Pakistan at a glance

Pakistan, being a warm area, is particularly sensitive to atmospheric changes since it is located in a geographical zone where temperatures exceed the global average. The nation is predominantly dry and semi-arid (approximately 60% of the land receives less than 250 mm of rain per year, with the

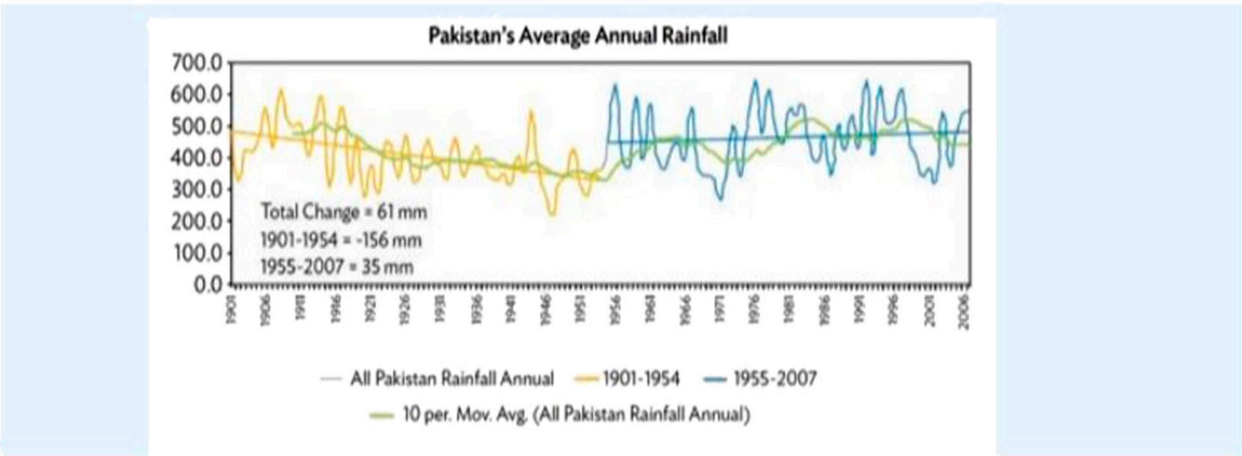


FIGURE 1
Historical precipitation in Pakistan, adapted from ADB (2017).

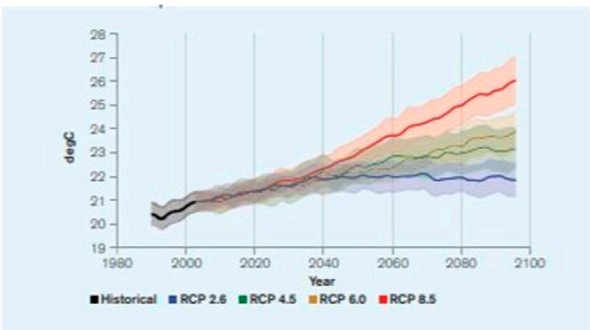


FIGURE 2
Historic and projected average annual temperature in Pakistan under RCP2.6 (blue) and RCP8.5 (red). The values shown represent the median of 30+ GCM model ensemble with the shaded areas showing the 10–90th percentiles.

remaining 24% receiving between 250 and 500 mm); the rivers are mostly supplied by Hindu Kush-Karakoram Himalayan glaciers. They are rapidly disappearing because of global warming; the economy is agrarian and hence particularly vulnerable (Syed et al., 2022). The variability of monsoon weather and rainfall each year has resulted in huge floods and widespread droughts in Pakistan in recent years. As a result of the problems, Pakistan's groundwater resources, storm surge security, energy security, and agricultural sectors are all jeopardized (Boone, 2008). According to Figure 1, mean rainfall in Pakistan's dry plains and the coastal belt has dropped by 10%–15% since 1960, leading to the continued deterioration of the country's wetlands and mangrove ecosystems. The majority of other regions have seen a slight increase, both during the monsoon and dry seasons.

Furthermore, rising temperatures have created a noteworthy shift in monsoon patterns as well as an increase in the number of hurricanes in northern Pakistan in recent years, with agricultural consequences. Pakistan is the world's sixth most susceptible country to climate change (Ahmed et al., 2020). Figure 2 shows the future projection of the rise in temperature in Pakistan. It can be seen that the future rise in average temperature in Pakistan is significantly greater than the world temperature which is a very alarming situation.

Climate abrupt changes have been a vital concern for Pakistan because of its faster-growing population and the resultant increase in urbanization (Anwar et al., 2020).

GHGs from the heavy use of fossil resources are recognized as the primary cause due to their influence on heat retention in the upper atmosphere. This increase in global temperature exacerbated the phenomenon of global warming, resulting in climate change worldwide consequences. Over 25 million people are employed in Pakistan's agriculture-based economy. Pakistan is ranked as the world's fifth most populous economy where the population growth rate is more than 2.83% (GoP, 2021).

In general, when agricultural output rises, so does industrial output, because agricultural and industrial output are inextricably linked (Graue, 1930). The link between the agricultural and industrial sectors has long-term implications since higher agricultural production leads to reduced prices and farm consolidation. The industrial sector makes use of extra manpower that the agricultural sector does not require (Lewis, 1972). According to the general economic growth theory, this process leads the entire economy to grow. In contrast, the short-run relationship is very different from the long-run relationship. Agricultural commodity price fluctuations are directly related to the general health of the economy and the expansion of the industrial sector. Reduced agricultural revenue

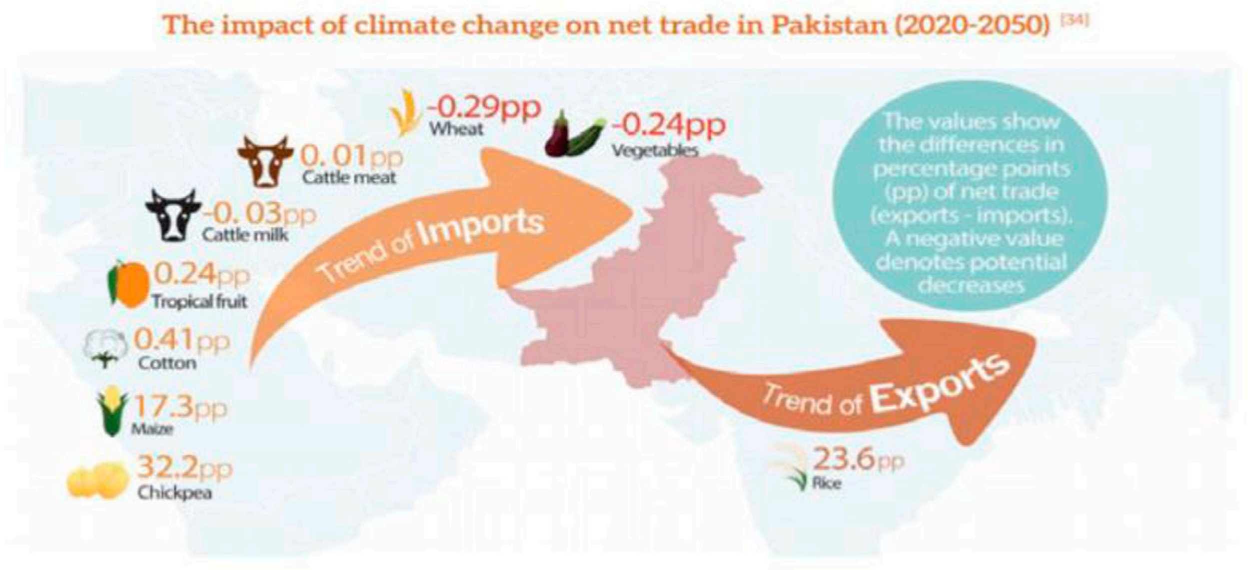


FIGURE 3
Climate knowledge portal (Chaudhary, 2017).

leads to lesser demand for industrial goods, and the economy suffers as a result. The importance of the agricultural sector in business cycles shows that business cycles are very much dependent on agricultural activities in economies.

The rising realization that Pakistan contributes the minimum to the environmental impact while suffering the most devastating consequences of climate change motivates Pakistan to understand the ramifications. This is due not just to economic losses associated with decreased agricultural output, but also to increases in sickness, mortality, and social instability. Countries face opportunity costs when they spend money on climate adaptation rather than on technological advancement or capital investment. We should take action to prevent human-caused climate change, as these changes have a significant impact on agricultural productivity. This is a highly concerning issue for developing countries whose economies rely on agriculture. The Figure 3 below depicts the climatic variance impact on agricultural trade through 2050 in Pakistan.

According to Naeem et al. (2012), Burke et al. (2015), Liu (2022), Liu and Wang (2022) the impact of climatic variation on economic growth can be asymmetric. Therefore, the main objective of this study is to investigate the asymmetric impact of CO2 and temperature on the economic production of Pakistan. In case of Pakistan there is rarely any study available that investigates the nonlinear relationship between climate change and economic growth. This study will also contribute to provide effective policies that will helps in the reduction of economic loss due to climate change. This research also provides the answers to the following questions: Are temperature, precipitation, and CO2 are important factors that effects Pakistan's economic growth? Do CO2 and temperature have asymmetric impact on economic growth of Pakistan?

2 Literature review

There is much disagreement on the primary drivers of climate change and the influence of climate change on global economic growth. The body of knowledge on the relationship between environmental sustainability and economic growth has developed dramatically. This section provides an updated assessment of how climate change impacts economies, as well as an evaluation of key empirical and theoretical literature on the relationship between climate change and economic development.

Wade and Jennings (2016) investigate the worldwide economic impacts of climate change. According to them, as global temperatures increase, rising operating expenses would harm the global economy, with studies suggesting a worst-case annual effect of 1% GDP growth. According to research, the impact would be disproportionately unfavourable for developing countries, and the long-term financial consequences of climate change can only be mitigated by cooperating to enact strong carbon emission restrictions. Berlemann and Wenzel (2018) explore the short- and long-run growth impacts of rainfall using a large panel dataset spanning more than 150 countries from 1951 to 2013. They discover extensive and highly strong empirical evidence for long-term negative growth consequences of rainfall deficits in poor and rising countries that are not driven by the Sub-Saharan African subsample. Stock's (2020) research on Climate Change, Climate Policy, and Economic Growth included temperature, CO2 emissions, and GDP. According to the study, rising temperatures cause a wide range of climatic changes, including droughts, hotter days, and more powerful rainfalls and storms, all of which vary locally. The principal driver of this warming is anthropogenic carbon dioxide (CO2) emissions from the combustion of fossil fuels. Baig et al. (2022) investigated the asymmetrical dynamic connection between climatic change and rice production in regard to other explanatory factors. On time series data from India from 1991 to 2018, the researchers employed the nonlinear autoregressive distributed lag (NARDL) model and the Granger causality approach. According to the NARDL findings, mean temperature has a detrimental long-term influence on rice yield while having a positive short-term impact. Furthermore, positive shocks in rainfall and carbon emissions have long-term and short-term negative and severe consequences on rice yield. In contrast, negative rainfall shocks have a significant long-term and short-term influence on rice yield. There is a feedback impact between mean temperature, decreasing rainfall, rising carbon emissions, and rice yield, according to the Granger causality test. Khan et al. (2020) assessed the economic impact of climate change-induced agricultural output loss in Pakistan using a combination of global climate, crop, and economic models. Climate change-induced reductions in wheat and rice crop productivity would cost Pakistan $19.5 billion in real GDP by 2050, according to the estimates, with commodities prices rising and domestic private consumption declining dramatically. However, the decline in agricultural output affects not only the economic agents working in the country's agriculture sector, but it also has a multiplier effect on the industrial and commercial sectors. A major increase in commodity prices would provide a huge challenge to the entire country's livelihood, especially for city dwellers. Kiley (2021) utilised quantile regressions to determine if climate change increases the likelihood of severe economic recession. Temperature has a significant and consistent influence on economic growth risks across all dimensions.

3 Methodology

3.1 Theoretical background

The current research used the Cobb-Douglas Production function for estimation for finding out the impact of climatic changes on economic growth. These effects are then added together to get an estimation of the overall shift in social wellbeing induced by climate change (Fankhauser and Tol, 2005; Niamir et al., 2020). Dell et al. (2008) integrated climate variations into the equation; this approach would be used as a benchmark in the ongoing study since it establishes a conceptual framework for including climate variations in the economic development model. Take into account the following model:

$$Y_{t=}e^{aTt} A_t\, L_t K_t \quad (1)$$

$$\frac{\Delta A_t}{A_t} = \beta T_t \quad (2)$$

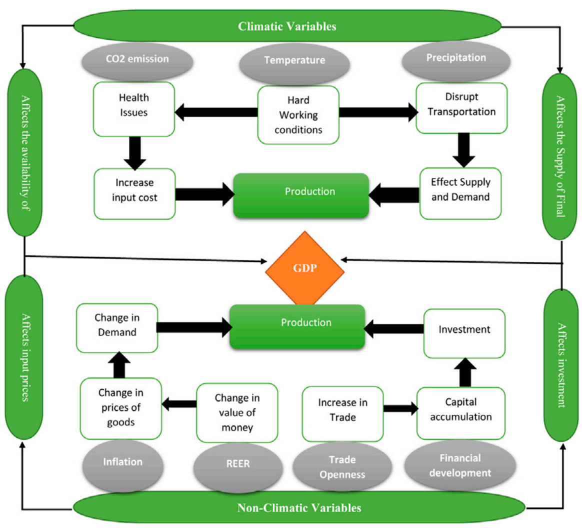
Where Y represents GDP, L represents labor force, A represents technology, and can alternatively be referred to as labor productivity, T represents climatic impacts, and K represents physical capital. The direct consequences of climate change on economic growth are captured in Eq. 1 while Eq. 3 captures the impact of climate on other factors that drive GDP growth indirectly. It is worth noting that Eq. 1 directly ties climate change to GDP, but Eq. 2 relates climate change to labor productivity, which in turn affects GDP growth. After taking logs of Eq. 1 and differencing concerning time, the following equation can be derived.

$$g_{t=}(\alpha + \beta)T_t - \alpha T_{t-1} \quad (3)$$

Where GDP growth rate is used, direct effects of climate change on economic growth are represented as α and indirect effects as β. This equation separates the direct and indirect effects of climate change. Both influence the initial pace of GDP growth. The direct impact reverses when the climate returns to its prior state.

3.2 Conceptual framework

The following conceptual frame has been developed based on past literature for current research.



Source: Author Own creation.

TABLE 1 Data sources.

S. No.	Variables	Sources	Comments
1	GDP growth rate (y)	SBP	GDP per capita
2	Population growth rate (POPG)	PES	Population growth rate
3	Carbon emission (Co2)	WDI	Carbon emission per kiloton (kt)
4	Consumer price index (CPI)	SBP	CPI
5	Temperature (MEANT)	CCP	Mean temperature (Celsius)
6	Trade openness (TOT)	SBP	Calculated by export + import/GDP
7	Financial development (FINDEV)	SBP	Domestic credit to private
8	Remittances (REMITT)	SBP	Remittances received from workers
9	Real effective exchange rate (RER)	SBP	RER
10	Precipitation (PER)	CCP	Precipitation (mm)

3.3 Variable description and data sources

Detail regarding different variables used in the current study is presented in Table 1 along with data sources.

3.4 Justification of explanatory variables

3.4.1 Real effective exchange rate

Real effective exchange rate (REER) is the measurement of domestic currency against the weighted average of several foreign currencies, divided by the price deflator. Depreciation of domestic currency makes exports cheaper and imports expensive and *vice versa*. The extent of price elasticity determines the effect of price movements in the services sector (Sahoo and Dash, 2014). Depreciation of REER results in an increase in exports for both developed and developing countries (Gnangnon, 2021). According to Kandil and Mirzaie, (2002) the REER affect the economic growth through various channels. The first channel affects the demand of the goods and services by raising imports and decreasing exports because of appreciation. As a result, aggregate demand is contracting. The second channel is that appreciation reduces demand for the dollar because agents expect the REER to recover to its expected steady-state value. We have used REER as a key independent variable for our model.

3.4.2 Remittances

Remittances (REM) are the transfer of a portion of a migrant's earnings in the form of cash or commodities to assist their family. The increase in remittances will increase the foreign reserves of the country and help in the appreciation of the currency. Mim and Ali (2012) through channels of saving and investment, remittances have a direct impact on the economic growth. Remittances can support the accumulation of human capital, implying that human capital is an effective avenue *via* which remittances influence the expansion of the GDP. The proxy variable used for remittances is Personal remittances received as a % of GDP which is also used by Munawar and Baig (2019) and Stojanov et al. (2019).

3.4.3 Trade openness

Trade openness (TO) is the sum of imports and exports normalized by GDP. The proxy variable used for Trade Openness is trade as a ratio of GDP (Keho, 2017). According to Wong (2007) trade openness impacts the economic growth through access to better and cheaper technology equipment, economies of scale, and spillover effects. The production of goods and services in an open economy can have access to foreign technology and innovation that result in a boost of production.

3.4.4 Inflation

An inflation is a situation of declining purchasing power of a specific country currency over a specific period.

3.4.5 Population growth

The population of Pakistan has grown at a rate of 2.1% due to an extremely high birthrate. As is well known, national income is divided by the whole population to determine per capita income. The population growth is shown in the low per capita income.

3.4.6 Mean temperature

The average air temperature throughout a specific time period, typically a day, a month, or a year, as measured by a thermometer that has been properly exposed. The mean temperature is often calculated for the year and for each month in climatological tables.

3.4.7 Carbon emission

Carbon dioxide emissions, also known as CO2 emissions, are those caused by the burning of fossil fuels and the production of cement and other goods. They also include gas flaring and carbon dioxide created during the use of solid, liquid, and gas fuels.

3.5 Econometric model and data analysis

The economic growth will be calculated using Eq. 4 which is the Supper Reduced form of the baseline model used is specified as:

$$Y_{t=}\beta_1 + \beta_2 RER_t + \beta_3 CPI_t + \beta_4 Remitt_t + \beta_5 FD_t + \beta_6 Popg_t + \beta_7 tot_t + \beta_8 CO2_t + \beta_9 MTEMP_t + \beta_{10} Prep_t + \varepsilon_t \quad (4)$$

Where Y represents GDP while RER, CPI, LTF, FD, Popg, CRM, TOT, CO2, MTEMP, and Prep denote real effective exchange rate, consumer price index, remittances, financial development, Population growth, and terms of trade, CO2 emissions, mean temperature, and precipitation respectively.

The current study used the NARDL model to estimate the asymmetric effect of climate change on economic growth. NARDL is the updated version of the Autoregressive Distributive Lag model (ARDL) of Pesaran et al. (2001).

The ARDL model was used to examine the symmetric influence of variables in both the short and long term, but it does not account for the asymmetric relationship between variables. By applying partial sum decomposition of the independent variables, NARDL can tolerate asymmetric effects in both long-run equilibrium and short-run dynamic coefficients. Because of its simplicity and ease of interpretation, the NARDL model is frequently utilized in the research in a variety of domains, including economics (Cho et al., 2006). The following ARDL equation shows the linear relationship between Climate change and economic growth:

$$\begin{aligned} Y_t = \eta_0 &+ \sum\nolimits_{i=1}^{q} \eta_1 (Y)_{t-1} + \sum\nolimits_{i=1}^{q} \eta_2 (RER)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_3 (CPI)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_4 (Remitt)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_5 (FD)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_6 (Popg)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_7 (TOT)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_8 (CO2)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_9 (MTEMP)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_{10} (Prep)_{t-i} + \mu_t \end{aligned} \quad (5)$$

Respecify the above equation above we get the ARDL Cointegration model equation as follows.

$$\begin{aligned} Y_t = \eta_0 &+ \sum\nolimits_{i=1}^{q} \eta_1 (Y)_{t-1} + \sum\nolimits_{i=1}^{q} \eta_2 (RER)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_3 (CPI)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_4 (Remitt)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_5 (FD)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_6 (Popg)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_7 (TOT)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_8 (CO2)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_9 (MTEMP)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_{10} (Prep)_{t-i} + \gamma_1 (Y)_t \\ &+ \gamma_2 (RER)_t + \gamma_3 (CPI)_t + \gamma_4 (Remitt)_t + \gamma_5 (FD)_t \\ &+ \gamma_6 (Popg)_t + \gamma_7 (TOT)_t + \gamma_8 (CO2)_t + \gamma_9 (MTEMP)_t \\ &+ \gamma_{10} (Prep)_t + \varepsilon_t \end{aligned} \quad (6)$$

Where q is the lag of independent variables. η = Short-term representation of Variables. γ = long-term representation of variables.

The analysis normally begins with a check of the order of integration of all variables to assure a non-spurious estimation and that no variable is integrated in order larger than one I(1); otherwise, the limits test for cointegration will be invalid. To avoid erroneous regression, the ADF unit root test established by (Dickey and Fuller, 1979) is used to assess the stationarity of time series data. Our model's variables are a combination of stationary at a level I(0) and non-stationary, integrated with order one. CMR, CO2, CPI, Meant, and Per are all stationary at a level I(0), but all other variables are I(1), with no I(2) variables.

Eqs 5, 6 show a symmetric connection between explanatory variables. Given the importance of non-linearity in that both positive and negative increases in MEANT and CO2 may have distinct effects. So, the NARDL model is more suited to reflect the asymmetric influence of these positive and negative changes (Shin et al., 2014). Climate change variables are split into MEANT POS and MEANT NEG, CO2 POS, and CO2 NEG in the NARDL technique. As a result, the model is as follows:

Decomposing variables

MEANT

$$POS_t = \sum\nolimits_{j=1}^{t} \Delta MEANT_j^{+} \sum\nolimits_{j=1}^{t} max\left(\Delta MEANT_j, 0\right) \quad (7)$$

$$NEG_t = \sum\nolimits_{j=1}^{t} \Delta MEANT_j^{-} \sum\nolimits_{j=1}^{t} min\left(\Delta MEANT_j, 0\right) \quad (8)$$

CO2

$$POS_t = \sum\nolimits_{j=1}^{t} \Delta CO_2{}_j^{+} \sum\nolimits_{j=1}^{t} max\left(\Delta CO_{2j}, 0\right) \quad (9)$$

$$NEG_t = \sum\nolimits_{j=1}^{t} \Delta CO_2{}_j^{-} = \sum\nolimits_{j=1}^{t} min\left(\Delta CO_{2j}, 0\right) > \quad (10)$$

As we are using a nonlinear framework in our study and there is a probability of nonlinear impact in the time-series data. Therefore, we make a nonlinear model as follows:

$$\begin{aligned} Y_t = \eta_0 &+ \sum\nolimits_{i=1}^{q} \eta_1 (Y)_{t-1} + \sum\nolimits_{i=1}^{q} \eta_2 (REER)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_3 (CPI)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_4 (Remitt)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_5 (FD)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_6 (TOT)_{t-i} \\ &+ \sum\nolimits_{i=1}^{q} \eta_7 (POPg)_{t-i} + \sum\nolimits_{i=1}^{q} \eta_8 CO2_{t-i}^{+} + \sum\nolimits_{i=1}^{q} \eta_9 (CO2)_{t-i}^{-} \\ &+ \sum\nolimits_{i=1}^{q} \eta_{10} (MEANT)_{t-i}^{+} + \sum\nolimits_{i=1}^{q} \eta_{11} (MEANT)_{t-i}^{-} \\ &+ \sum\nolimits_{i=1}^{q} \eta_{12} (Prep)_{t-i} + \gamma_1 (Y)_t + \gamma_2 (REER)_t + \gamma_3 (CPI)_t \\ &+ \gamma_4 (Remitt)_t + \gamma_5 (FD)_t + \gamma_6 (POPg)_t + \gamma_7 (TOT)_t \\ &+ \gamma_8 CO2_t^{+} + \gamma_9 CO2_t^{-} + \sum\nolimits_{t}^{q} \gamma_{10} (MEANT)_{t-i}^{-} \\ &+ \sum\nolimits_{t}^{q} \gamma_{11} (MEANT)_{t-i}^{-} + \gamma_{12} (Prep)_t + \varepsilon_t \end{aligned} \quad (11)$$

TABLE 2 Results of PP and ADF test.

Variables	PP test statistics		ADF test statistics		Order of integration
	Level	1st difference	Level	1st difference	
LGDPER	0.0338	−6.115	−0.1015	−6.0911	I(1)
	−0.9562	(0.000)***	−0.9425	(0.000)***	
CO_2	−1.9652	−2.7014	−1.9652	−2.708	I(1)
	−0.3005	(0.0827)*	−0.3005	(0.0815)*	
CPI	−3.2148	−7.3278	−3.0999	−7.2776	I(0)
	(0.0262)**	(0.000)***	(0.0344)**	(0.000)***	
MEANT	−3.0549	−11.8676	−2.9928	−5.3297	I(0)
	(0.0381)**	(0.000)***	−0.0439	(0.0001)***	
PER	−6.9943	−44.5787	−6.9967	−11.6884	I(0)
	(0.000)***	(0.000)***	(0.000)***	(0.000)***	
POPG	−0.3178	−2.8795	−0.3107	−5.3977	I(1)
	−0.9133	(0.0567)*	−0.9139	(0.000)***	
LTOT	−1.5252	−5.7332	−1.4912	−5.7328	I(1)
	−0.511	(0.000)***	−0.528	(0.001)***	
LFINDEV	−1.6145	−4.3681	−1.2218	−4.3421	I(1)
	−0.4662	(0.001)***	−0.6556	(0.000)***	
LREMITT	0.5586	−4.9691	0.7214	−4.9668	I(1)
	−0.9868	(0.000)***	−0.9912	(0.000)***	
LRER	−2.1482	−5.5065	−2.175	−5.4682	I(1)
	−0.2277	(0.000)***	−0.2181	(0.000)***	

Note: (*), Significant at the 10%; (**), Significant at the 5%; (***), Significant at the 1%; no, not significant. The values in the Parenthesis () are the *p*-values.

TABLE 3 Bound test.

F-bounds test				
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	11.49204	10%	1.76	2.77
k	11	5%	1.98	3.04
		2.50%	2.18	3.28
		1%	2.41	3.61

Where,i = lag identityt = timeη_0 = Interceptλ = Long run coefficient

4 Results and discussion

4.1 Testing of unit root

In this study, we employed Phillips and Perron's (1988) (Fisher-PP) and Augmented Dicky Fuller (ADF) tests to examine the propensity of a unit root test across a series of data. Table 2 shows the results of unit root testing. According to the findings, variables such as CPI, MEANT, and PER are stable at the level in both tests, indicating that they do not require differencing due to zero-order integration. However, after initial differencing, the other variables, which included GDPER, CO2, FINDEV, REER, REMIT, and TOT, remained steady.

4.2 Autoregressive distributive lag model co-integration—the bound test

To study the cointegration connection between variables by imposing zero constraints on one lag variable. As indicated in Table 3, the computed F-statistics is eleven, which is larger than the upper bond values I(1) critical value (i.e., 2.77) at a 10% significant level. As a result, the null hypothesis of no cointegration is rejected, implying that GDP growth, carbon emissions, precipitation, average temperature, trade openness, inflation rate, Population growth rate, financial development, real effective exchange rate, and remittances have a long-run connection.

4.3 Short-run results

Table 4 depicts the short-run results of the NARDL model. According to the results, CO2_NEG and CO2_ POS have

TABLE 4 Short-run results.

Variable	Coefficient	Std. error	t-statistic	Prob.
C	−26.9470	6.1891	−4.3540	0.0073
LGDPER(-1)	−1.9310	0.4061	−4.7551	0.0051
CO2_POS(-1)	−1.9359	0.3159	−6.1290	0.0017
CO2_NEG(-1)	−2.6290	0.6098	−4.3112	0.0076
CPI(-1)	0.0058	0.0029	2.0119	0.1004
MEANT_POS(-1)	0.1094	0.0314	3.4842	0.0176
MEANT_NEG(-1)	−0.1315	0.0527	−2.4936	0.0549
PER(-1)	0.0002	0.0003	0.7738	0.4740
POPG(-1)	0.5626	0.1622	3.4689	0.0179
LTOT(-1)	7.7553	1.9225	4.0339	0.0100
LFINDEV(-1)	0.9684	0.2012	4.8138	0.0048
LREMITT(-1)	0.3626	0.1151	3.1511	0.0253
LRER(-1)	0.6729	0.2197	3.0630	0.0280
D(LGDPER(-1))	0.6766	0.2986	2.2660	0.0728
D(CO2_POS)	−0.8591	0.2756	−3.1176	0.0263
D(CO2_POS(-1))	0.3862	0.1963	1.9675	0.1063
D(CO2_NEG)	−0.2318	0.1854	−1.2503	0.2665
D(CO2_NEG(-1))	2.9680	0.6863	4.3250	0.0075
D(CPI)	0.0045	0.0015	2.9402	0.0323
D(CPI(-1))	0.0017	0.0016	1.0828	0.3283
D(MEANT_POS)	−0.0145	0.0190	−0.7626	0.4801
D(MEANT_POS(-1))	−0.0715	0.0207	−3.4609	0.0180
D(MEANT_NEG)	0.0315	0.0168	1.8816	0.1186
D(MEANT_NEG(-1))	0.0838	0.0259	3.2329	0.0231
D(PER)	0.0002	0.0001	2.2715	0.0723
D(PER(-1))	0.0002	0.0001	1.5185	0.1894
D(POPG)	0.3084	0.3039	1.0147	0.3568
D(POPG(-1))	−0.7240	0.3332	−2.1727	0.0819
D(LTOT)	−1.7597	0.9667	−1.8203	0.1284
D(LTOT(-1))	−7.2193	1.6713	−4.3195	0.0076
D(LFINDEV)	−0.0628	0.1606	−0.3909	0.7120
D(LREMITT)	0.1713	0.0944	1.8156	0.1291
D(LREMITT(-1))	−0.1094	0.0474	−2.3080	0.0691
D(LRER)	−0.0183	0.1977	−0.0925	0.9299
CointEq(-1)	−0.8415	0.0220	−38.2838	0.0000

significant effects on the GDP level. 1 unit increase in the carbon emissions is likely to decrease GDP growth by 1.935 units, Ejuvbekpokpo (2014) found the same as our findings that CO2 and economic growth are negatively related to each other. The increase in CO2 emission effects the health of the labor, which as a results cause decline in the productivity of labor and negatively effects GDP as well. Further, a 1 unit decrease in the mean CO2 emissions also reduces the GDP by 2.6290. Ghosh (2010) found that the decrease in CO2 emission will likely diminish the GDP growth. The CO2 at a certain level is feasible for the agricultural production however lower than that will affect the agricultural production. On the other hand, MEANT_POS increased GDP by 0.1094, and MEANT-NEG decreases GDP by 0.1315. Since excessive cold can impede some activities just as much as extreme heat, greater temperatures in colder regions or during colder seasons may boost economic activity Colacito et al. (2018). Other controlled variables including CMR, CPI, TOT, POPG, and PER show a positive impact on GDP growth. Further, CO2_POS, LFINDEV, LREER, LREMITT, and LTOT become significant after one lag period. The results of the ECM model show that the value of the ECM coefficient is negative and significant (−0.706). In practical results, the value of ECM should be negative and significant in the long run relationship which can be seen above indicating the

TABLE 5 Long-run results.

Variable	Coefficient	Std. error	t-statistic	Prob.
CO2_POS	−1.0025	0.178	−5.63	0.0024
CO2_NEG	−1.3615	0.375	−3.63	0.0150
MEANT_POS	0.0566	0.017	3.24	0.0229
MEANT_NEG	−0.0681	0.017	−3.98	0.0105
PER	0.0001	0.000	0.73	0.5006
CPI	0.0030	0.001	2.74	0.0408
POPG	0.2913	0.063	4.66	0.0056
LTOT	4.0162	0.858	4.68	0.0054
LFINDEV	0.5015	0.118	4.26	0.0080
LREMITT	0.1878	0.029	6.37	0.0014
LRER	0.3485	0.086	4.05	0.0098
C	−13.9548	3.060	−4.56	0.0061

cointegration among variables. This value of ECM indicates that around 84% of deviations are adjusted per year. This shows the stability, and the speed of adjustment is quick. In other words, the ECM coefficient is very large which means that the adjustment of short deviation around the long run time path is very quick. Anyhow the ECM model is considered stable, and the endogenous variables are the elasticities that indicate the short-run impact on services sector output. The value of ECM (−0.8415) indicates that the last year shocks disequilibrium as compared to the long-run equilibrium in the present year.

4.4 Long-run results

Table 5 shows the long-term results of the NARDL model. Empirical results depict that there is an asymmetric association between climatic factors (temperature and Carbon emissions) and economic growth. According to our findings, CO2 emissions have asymmetry in magnitude, but MEANT has asymmetry in sign. The CO2 emission coefficient demonstrates that increases and decreases in CO2 emissions hurt economic development, i.e., a 1 unit increase in the carbon emission will likely decrease the GDP growth by 1.0025 percent whereas a 1 unit decrease in the carbon emission caused 1.35 percent to decline in the GDP growth. These findings are consistent with those of Porter and Brown (2009), who discovered that carbon emissions had a negative and substantial influence on economic growth. They asserted that the negative impact is due to decreased land and labor productive capacity because of rising carbon emissions. The negative impact of CO2 on the level of GDP in the Pakistan economy is caused by a decrease in aggregate output. Our findings on CO2 emissions' positive relationship with GDPG are corroborated by literature, which indicated that because of globalization, both companies and individuals will develop quicker. As a result, agricultural production must increase to provide food security and a continuous supply of raw materials to the industrial sector (Schneider and Smith, 2009). As a result, higher agricultural production raises carbon dioxide emissions (Celikkol Erbas and Guven Solakoglu, 2017). Indeed, improper agricultural practices such as agricultural production in unsuitable areas to increase output, pesticides and chemical fertilizers, irrigation, soil processing, mistakes in plant hormone use, stubble burning, and dumping of unsuitable animal waste into the soil all contribute to increased CO2 emissions from crop production (Waheed et al., 2018). So, an increase in agricultural production increases GDPG and CO2 emissions as well.

Climate change is a socioeconomic as well as an environmental issue. Too much heat or cold can have an impact on human behavior, efficiency, and, worst of all, mortality. MEANT coefficient shows that asymmetric effect on economic growth.1 unit increase in temperature increases economic growth by 0.0566 percent whereas 1 unit decrease in temperature decreases economic growth by 0.0681 percent. According to (Colacito et al., 2018) positive impact of the rise in temperature on GDP growth is due to its variance from region to region. Higher temperatures in colder regions or during colder seasons may have a positive effect on economic activity because the extreme cold can be just as difficult to perform as extreme heat. So, the rise in temperature in colder areas could be more productive for economic activities due to less effect of cold. The positive impact of the temperature rise is also due to boost of some industries in hotter weather, like rising in the demand of refrigerator, air-conditions, Increased summer temperatures have a positive impact on some industries, such as rise in the demand of refrigerator, air-conditions, the solar industry, utilities, and mining, may benefit from increased energy consumption during hotter days. Our study is also supported by the results of Berge et al. (2017). Our result further documented the MEANT_NEG pose a negative impact on economic growth. Several well-documented studies show that extreme weather hurts agricultural yields and worker productivity. These have an impact on household welfare and may lead to an increase in poverty incidence (Lee et al., 2016). The decline in the temperature hurts the agricultural sector. Weather uncertainty in Pakistan causes loss of crops due to which the output of agricultural products declines. Heavy rainfalls in the region cause a decline in temperature and many times it causes flooding that as a result destroys the crops. According to Burke et al. (2015), the regions with already cold weather are also productive and they yield more production but when temperatures decline more than a certain level it causes a decline in the output. Further, PER causes a positive but insignificant effect on economic growth. Past studies (Porter and Brown, 2009; Akram and Hamid, 2015) also showed the positive link between precipitation and economic growth which primarily is caused by the agricultural sector.

Our findings show that there is a positive relationship between CPI and economic growth, as a1 unit increase in CPI will cause a 0.0030% increase in GDPG, thus as the rate of inflation rises, GDP Declines (Asif, 2013). Our findings are consistent with those of Hussain and Malik (2011), who discovered that both factors had a positive and substantial influence on each other. Our findings are consistent with the Tobin portfolio-shift effect, which states that a high inflation rate causes consumers to invest more in physical capital while decreasing their real balance holdings.

Our research also shows that POPg had a beneficial and considerable impact on economic growth. Our findings are consistent with those of Ali et al. (2013) and Afzal (2009), who found that population expansion had a beneficial influence on economic growth. According to them, population expansion is not a serious concern; rather, it may aid economic growth because of the large workforce available and the division of labor.

In our analysis, LTOT plays a significant role in promoting GDP growth. The co-efficient of variable LTOT reveals that it has a significant positive impact on GDPPER. The coefficient is significant at the 1% level, implying that increasing LTOT boosts growth. The TOT co-efficient is high, indicating that a 1% change in LTOT results in a 4.0162 percent increase in GDP growth. As a result, developing countries like Pakistan must accelerate trade liberalization to achieve high economic growth. They should not be concerned about the weak arguments in favor of protectionism. This result agrees with Ghosh and Phillips (1998), Leyaro (2015), and Tahir and Khan (2014).

The growth of GDP is positively impacted by financial development, as is to be expected. An increase in financial development by 1% causes an increase in GDP growth by 0.5015%. The availability of financing is extremely important for GDP growth. The increase in finance will lead to an increase in investment and production and as a result the GDP will grow. Therefore, it is advised that policymakers extend the lending of finance to highlight its contribution to economic growth (Tahir et al., 2021).

On the other hand, the LREMMIT indicates a favorable and large impact on the output of the services sector. Results indicate that a 1% increase in LREMMIT causes a 0.1878% increase in the GDP. Empirical data are currently accessible that support our findings. Numerous research has discovered the beneficial effects of remittances on GDP, including Lucas (2005) and Glytsos (2002). Like this, the study by Catrinescu et al. (2009) demonstrates that REMMIT has a favorable effect on output productivity. They discovered that the REMITT influences the GDP through consumption and investment. Investment rises by 3% because of the growth in remittance revenue (Osili, 2004). Remittances from overseas raise the beneficiaries' standard of living, which increases demand for and investment in the economy (Mim and Ali, 2012). According to a study by Woodruff and Zenteno (2001), 20% of remittances are used to fund microenterprises that experience rapid development and productivity. Our investigation suggests similar findings to those of these studies.

TABLE 6 Granger causality tests.

Null hypothesis	F-statistic	Prob.
LREER does not granger cause LGDPER	4.677	0.016
LGDPER does not granger cause LREER	1.094	0.346
LREMITT does not granger cause LGDPER	3.312	0.048
LGDPER does not granger cause LREMITT	0.315	0.732
LTOT does not granger cause LGDPER	0.054	0.947
LGDPER does not granger cause LTOT	1.654	0.206
PER does not granger cause LGDPER	0.758	0.476
LGDPER does not granger cause PER	0.102	0.904
POPG does not granger cause LGDPER	5.629	0.008
LGDPER does not granger cause POPG	4.992	0.012
CMR does not granger cause LGDPER	0.221	0.029
LGDPER does not granger cause CMR	0.691	0.508
CO2 does not granger cause LGDPER	0.317	0.731
LGDPER does not granger cause CO2	4.056	0.026
CPI does not granger cause LGDPER	0.271	0.048
LGDPER does not granger cause CPI	0.058	0.944

The results further indicate the positive impact of LRER. A 1%increase in the value of the rupee is likely to raise GDP growth by 0.3485%. A stronger domestic currency encourages businesses to adopt more advanced technology to boost production and, consequently, profits by increasing imports of the machinery and raw materials required for the development and growth of the economy. The opportunity to purchase cheaper raw materials encourages an expansion in production. These findings concur with those of Johnson and Koyama (2017).

4.5 Granger causality test

Table 6 shows the results of granger causality test. It is observed that unidirectional causal relationship was running from LGDPER, LREER, LREMITT, LTOT, PER, POPG, CMR, CO2, CPI. Hence these causal relationships support the elasticity of NARDL for each series.

4.6 Stability test

CUSUM and CUSUM of the square test were initially presented by Brown et al. (1975). This test is based on a plot of the sum of recursive residuals. The plotting charts in this test show two straight red lines. While one blue line is between these two, red lines represent the percentage of the critical link. If blue lines cross red lines, then we refused each of the predicted

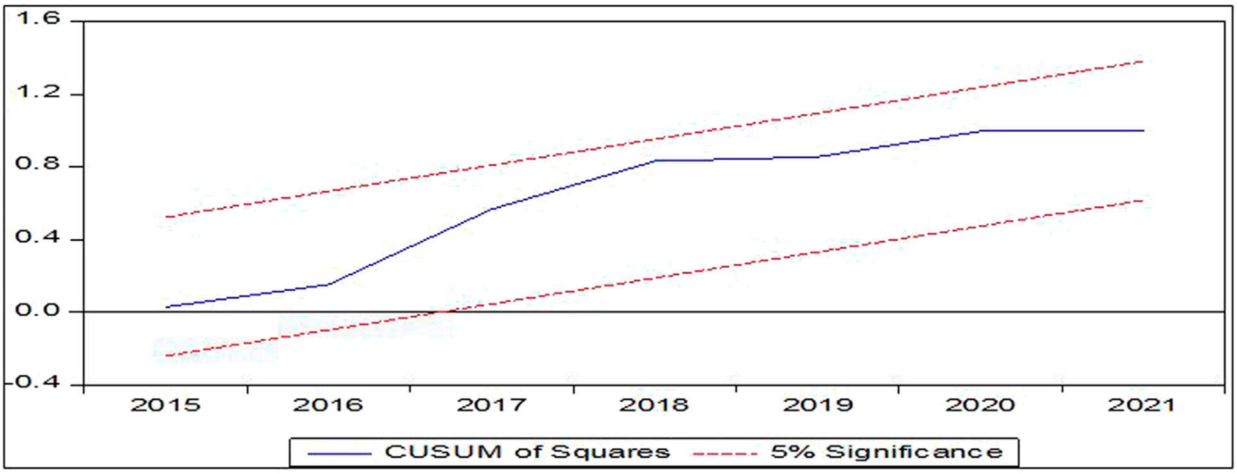


FIGURE 4
CUSUM square graph.

variables which suggests that our data is nonlinear. However, if the plot stays inside two straight lines, we do not reject projected variables which indicate that our data is linear. CUSUM test identified us to indicate whether the coefficient of the variables is changing systematically or not, however on the other hand cumulative test helps to show if the coefficient of regression is changing unexpectedly. CUSUM Square graphs have been illustrated in Figure 4. Because the plots stay between the critical lines at a 5% level of significance, we infer that the model is stable. Hence, we must assume that parameters are also stable because the blue line is existing inside the red line. CUSUM of squares is inside the critical limits of 0.05% which shows the structural stability of the model and overall goodness of fit.

5 Conclusion

It is worth noting that the physical elements of Pakistan cause a broad variety of climate changes. This climate volatility may have an impact on Pakistan's economic growth due to significant rainfall at one time and a drought condition at another, as well as floods and rising temperatures. As a result, climate change has had a negative impact on several areas of the economy. It is critical to understand the potential influence of climate change on economic growth in order to develop appropriate mitigation techniques and policies. In light of these considerations, the current study conducted time series research on the asymmetric relationship between climate change and economic growth in Pakistan. For this, we made use of the annual time series data collection for the years 1980 through 2021. The findings indicate that CO2 and MEANT have an asymmetric influence on economic growth. CO2 emissions have a negative long-term influence on GDP growth, but precipitation has a favorable long-term benefit. The mean temperature coefficient demonstrates that both increases and decreases in mean temperature are expected to favorably benefit Pakistan's economic growth. The negative effects of CO2 result from reduced labor and land productivity due to an increase in carbon emissions. The detrimental effects of a decline in total output on Pakistan's economy's GDP level. As a result of the nation's trade liberalization, more and more affordable used cars are being imported. As a result, the number of metric tons of automotive emissions has increased, endangering the environment. Plant fumes and portable generators, which are also imported in significant numbers because of the country's inconsistent electricity supply, are other sources of carbon emissions. Our findings are validated by (Azomahou et al., 2006; Ajmi et al., 2015; Salahuddin and Gow, 2016; Dogan and Aslan, 2017). However, the mean temperature coefficient indicates that both a rise and a drop in mean temperature are expected to have a favorable impact on Pakistan's economic development. However, the impact of the temperature fall on GDP growth is minimal. Our research indicates that a 1 unit rise in temperature can result in 0.0566 units rise in GDP. According to Riccardo et al. (2018), the fact that the influence of temperature rise on GDP growth varies by location is what accounts for this. In fact, because extreme cold can be just as difficult to perform as excessive heat, greater temperatures in colder places or during colder seasons may have a favorable impact on economic activity. Therefore, the economic operations in colder regions may be more productive as a result of the cold's diminished effects. According to the study findings, if climate change is not regulated, Pakistan's economic growth will be significantly curtailed. It argues for the need for a coordinated and comprehensive strategy addressing the implementation of prevention measures to control climate change because climate change will have a large negative influence on economic growth if it is not handled. Reduced economic growth will also result in a reduction in social welfare. Even though the poor contribute little to climate change, they bear the brunt of its consequences due to their reliance on agribusiness and inability to pay for preventative and mitigation measures. As a result, climate change mitigation is critical not just for economic growth but also for human well-being. However, Pakistan can only do so much to prevent climate change because its contribution to GHG emissions is modest in comparison to developed nations. Hence, two types of policy recommendations were presented. On the national level, The Pakistani government must increase tree planting projects and safeguard greenery at all costs. The problem is expected to worsen as the temperature rises and the population grows. Farmers must be taught cutting-edge agricultural and horticulture practices. On an international level, there is a need for an international policy regarding the adoption of mitigation strategies to control climate change.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/country/pakistan, https://www.sbp.org.pk/departments/stats/pakEconomy_HandBook/index.htm.

Author contributions

NK: conceptualization, data collection, and writeup. AF: analysis and review. KA: methodology and review. JK: data curation and proofread.

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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Optimal decision-making model for selecting residential green building technologies in China

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China is expected to have an annual demand of 1 billion square meters of new residential floor areas in the next few years. Housing developers have adopted various green building technologies (GBTs) in building designs to meet the constantly rising green building (GB) standards. However, they often ignore users' satisfaction and perception of these GBTs and doubt the cost-benefit assessment of GBTs. This study first constructed GBTs commonly used in residential construction in the Yangtze River Delta region, China. In particular, it adopted the Kano model and the Customer Satisfaction Coefficient (CSC) model to conduct questionnaire surveys on 171 Ningbo households to analyze the differences between developers' and users' perceptions of GBTs. Further, a zero-one integer programming (ZOIP) approach was used to build an optimal decision-making model for housing developers to select GBTs that take into account developers' incremental cost and benefit assessment. The results showed that residents focus on technologies related to comfort and health issues, followed by energy-efficient technologies with lower costs. High-cost and low-scoring GBTs, such as new air systems and Low-E center louvered glass, will be excluded. The decision model clarifies the differences between developers' and users' perceptions of GBTs and effectively assists developers in rationalizing the selection of GBTs. Furthermore, it is suggested that the proposed model can be widely applied to other projects in different regions in the future to promote GB markets in China.

KEYWORDS

green building (GB), technology selection, kano model, customer satisfaction coefficient (CSC), zero-one integer programming (ZOIP)

Introduction

Global warming and energy consumption have become the major environmental issues in the world today. Among many industries, the construction industry tops the list with 40% energy consumption (WBCSD, 2008) and generates 30% of greenhouse gases (UNEP, 2009). According to statistics, nearly 30% of China's energy consumption comes from the construction sector (Feng et al., 2014), with building operations accounting for 25% of total energy consumption and carbon emissions from building materials, reaching

15% of total emissions. By the end of 2019, the total floor area of residential buildings in China has reached 28.2 billion square meters. In addition, the number of completed residential building units has reached 5.97 million in 2020. It is speculated that from 2022 to 2030, China will still need 1 billion square meters of residential construction each year to meet housing needs due to high urbanization (China Building Energy Efficiency Annual Development Research Report 2021). These new homes will be mostly concentrated in the Yangtze River Delta region, where the population is constantly flowing in.

The further implementation of GBs has become one of the key policies of the Chinese government to reduce energy consumption. In 2021, the Chinese government planned to achieve carbon peaking by 2030 and carbon neutrality by 2060. To this end, the government has proposed many strict regulations for the construction industry to fully implement GB standards for new buildings in urban areas by 2025. However, in the practice of residential GBs in China, developers often blindly pile up advanced energy-efficient technologies for acquiring GB certification and ignore the actual benefits and return on the investment of these technologies (Lu et al., 2018). Consequently, many technologies and equipment are left unused, and there are even cases where tenants change the original design after occupancy due to the lack of GBT awareness or based on more cost considerations. For developers, the practical challenge lies in providing GBTs that meet users' needs under limited costs to enhance the competitive advantage of companies in the green building market.

A number of existing studies have explored GBTs and their impact on building energy management decisions. For example, Juan et al. (2010) developed a hybrid approach based on genetic algorithms (GA) for sustainable office building renovation and energy performance improvement. Ascione et al. (2015) proposed a new methodology for cost-optimal analysis by means of the multi-objective optimization based on GA for building energy performance. Seyedzadeh et al. (2020) presented a data driven model based on machine learning techniques improved by multi-objective optimization to predict building energy loads. Wu et al. (2018) integrated the multi-objective optimization technique with the comprehensive evaluation method technique of renewable energy systems in the building. Gossard et al. (2013) presented the multi-objective optimization of a building envelope for thermal efficiency using GA and artificial neural network.

The review of previous studies on GBTs revealed three major research gaps. First, only a few researchers have explored the users' evaluation and feelings about the GBTs. Second, many studies have addressed the potential and importance of application of simulations and optimization approaches on GBs, and most of these studies were operated from the designers' and experts' perspectives, rarely taking into account users' expectations of the technology. Third, from the developer's point of view, the relationship between GB benefits and technology cost in the selection of GBTs is less explored. Hence, the research questions of this study are as follows:

- What are the users' preferences for GBTs applied on GB projects?
- How can developers provide GBTs that meet user needs under a limited budget according to user preferences?
- How can developers conduct cost-benefit assessments for GBTs to enhance the advantages of green building projects?

To address the above research questions, this study presents a systematic optimal decision model suitable for residential GBTs in the Yangtze River Delta, China. Firstly, based on the local GB assessment standards, a series of residential GBTs have been formed by combining the common technologies of green settlements in the Yangtze River Delta over the past 3 years. Secondly, a neighborhood to be developed in Ningbo, China was selected. Then, the questionnaire based on the Kano model was distributed to the residents of its surrounding green neighborhoods. Subsequently, the Customer Satisfaction Coefficient (CSC) analysis was conducted on the questionnaire results to clarify the user preference attributes of each GBT. Finally, zero-one integer programming (ZOIP) was applied in this project to find the optimal strategy for selecting GBTs considering technology cost, user preference, and developer budget. In addition, this optimal decision model was tested using sensitivity analysis, after which, the maximum improvement efficiency of the optimal budget was explored, thus promoting the most efficient use of the budget and reducing ineffective design and construction costs.

Review of green building technology research

The green building evaluation system has been established and developed in many countries since the 1990s. Up to now, there have been more than 600 rating systems. *Building Research Establishment Environmental Assessment Method* (BREEAM) in the United Kingdom is considered to be the first assessment system. *Leadership in Energy and Environmental Design* (LEED) in the United States has become the most widely used evaluation system in the world because of its clear evaluation mechanism. In addition, *Deutsche Gesellschaft für Nachhaltiges Bauen e.V.* (DGNB) of Germany, *Haute Qualité Environnementale* (HQE) of France, Green Star of Australia, Green Star of New Zealand, *Green Mark* of Singapore, *Comprehensive Assessment System for Built Environment Efficiency* (CASBEE) of Japan and other systems are used to evaluate green building performance in different countries (Doan et al., 2017).

Under the different green building evaluation systems in different regions, many studies have successively focused on the application and development of GBTs and their impact on the environments in different climate conditions. For example, Huang et al. (2012) evaluated the sustainability of 11 energy-efficient technologies in the Chinese construction industry based on a multi-attributive assessment methodology—the results of which can be used to guide the development of regional projects. Dangana et al. (2013) developed a decision-making system to help retailers and building professionals define and evaluate options for sustainable technology solutions. Ahmad et al. (2016) combined a hierarchical analysis (AHP) of an interview study of 30 technical professionals for the optimal selection of pre-design GBTs. Juan et al. (2010) developed an integrated decision support system to assess existing office building conditions and to recommend an optimal set of sustainable renovation actions, considering trade-offs between renovation cost, improved building quality, and environmental impacts. Nguyen et al. (2017) argued that developers and designers should consider whether conditions and incorporate sustainability measures into the life cycle of GB projects at the early stage of building design. From the above literature, it can be found that past research generally believed that the selection of GBTs should be introduced in the early design stage. In addition, the existing GBTs studies focus more on the energy efficiency of technologies and the impact of GBTs on users and costs was less discussed (Ge et al., 2020).

Many researchers have pointed out that the adoption of GBTs may increase GB costs (Mapp et al., 2011; Tatari & Kucukvar, 2011; Juan et al., 2017). These additional costs incurred in adopting GBTs can be defined as incremental costs (Zhang, Wu, & Liu, 2018); for instance, Ge et al. (2018) selected 276 GB projects in China and evaluated the incremental cost of GBTs according to different building areas and types. The results showed that the incremental cost of GBTs was less than 2% of the total construction cost, and this cost will increase with the GB certification level. Although the cost of GB has increased, it can also bring some benefits. According to Zhang et al. (2018), the benefits of incremental costs mainly include reduced operating costs, improved comfort, health, and productivity, improved corporate reputation, positive environmental externalities, and increased GB market value. As far as developers are concerned, the green premium to improve corporate reputation and increase the market value of GB is the main driving force behind the implementation of GB. However, the relationship between users' preferences for GBTs and the incremental cost developers are willing to invest has rarely been studied.

According to the above literature and the identified research gaps, there are still some important issues and questions in GBT studies. Firstly, what are the preferences of users and the market for GBTs? On the other hand, from a developer's perspective, how should the cost-benefit assessment of these preferred GBTs be measured in the GB projects?

Residential green building technologies in the Yangtze River Delta, China

China's GB standards began with the assessment standard for green buildings (GB/T50378-2006) implemented in June 2006 (Zhang et al., 2018). In August 2007, the Ministry of Construction released the GB Evaluation Technical Regulations (for trial implementation) and the GB Evaluation Management Measures. Following Beijing, Tianjin, Chongqing, and Shanghai, more than 20 provinces and cities issued local standards, widely promoting GB standards (Li et al., 2021). As one of China's most economically developed regions, the Yangtze River Delta is one of the most active regions for GB implementation. In order to achieve its carbon peak and carbon-neutral goals, the Chinese government has increased its promotion of GBs and proposed the Carbon Reach Action Plan by 2030, requiring the full implementation of GB standards for new buildings in urban areas by 2025. In previous developments, many developers have invested in energy-efficient technologies to meet China's GB certification, blindly "(piling) on" technologies to meet the standards (Lu et al., 2018). Therefore, it is not difficult to imagine that more developers will invest in more diverse forms of technology to meet the more stringent GB energy efficiency standards in the future.

The latest version of China's Assessment standard for GB (GB/T50378-2019) sets certification requirements for GBs in terms of six major components: safety and durability, health and comfort, the convenience of living, and resource conservation, environmental livability, and improved innovation. Since applying GBTs has climatic and regional differences, the Yangtze River Delta is considered cold winter and hot summer region in the building climate zoning of China. Therefore, this study selected 13 residential projects in the Yangtze River Delta that have been certified as GBs in China in the past 2 years Table 1 presents a summary of the 21 technologies commonly used in GBs (certified) in residential projects.

Materials and methods

According to the purpose of the research, this study attempts to explore the user preferences for GBTs and the cost-benefit analysis of GBTs in GB projects. In view of user preferences, many previous studies have proposed various qualitative and quantitative methods for mining user needs. Qualitative methods focus on understanding user needs through observation, interview, and user experience analysis (Park et al., 2013), while quantitative methods have attracted more attention in recent years by using the Kano model to classify and rank user needs, which has been widely used in various fields (Juan

TABLE 1 GBTs for green settlements in the Yangtze River Delta.

Dimensions of GB standard in China	GBTs in residential GB projects	
Safe and durable	#1	Advanced Environmental Durable Decoration
Health and comfort	#2	High performance sound insulation materials
	#3	Adjustable external shading
	#4	Air purification new air system
Convenience of life	#5	Accessible design
	#6	Energy consumption monitoring system
	#7	Intelligent Air Monitoring System
Resource conservation	#8	Energy-saving air conditioning system
	#9	Low-E center louvered glass
	#10	High-efficiency heat and cold source system (solar water heater)
	#11	High-performance envelope (exterior wall insulation)
	#12	Energy-saving electric lights, elevators, and other electrical equipment
	#13	Efficient water-saving sanitary ware
	#14	Water-saving green irrigation technology
	#15	Comprehensive recycling of rainwater
Livable environment	#16	Community three-dimensional greening
	#17	Permeable pavement and green stormwater infrastructure
	#18	Green Roof
Improvement and Innovation	#19	The proportion of prefabricated parts used to meet the standard
	#20	BIM Technology
	#21	Green Construction and Management

et al., 2019; Lu & Juan, 2021; Xu & Juan, 2021). As for cost-benefit analysis, the zero-one integer programming (ZOIP) method, an important branch of management science, is suitable for dealing with the optimization problem of scheme selection under a limited budget, and has mature applications in the construction field (Juan et al., 2021). Therefore, this study adopts these two methods to explore user preferences for GBTs and the cost-benefit analysis respectively.

Kano model and customer satisfaction coefficient

The Kano model, a popular approach in product and service design, was proposed by Noriaki Kano in 1984, which can effectively identify and classify user requirements and rank them optimally. In this study, the Kano model is used to identify and classify users' preferences toward GBTs summarized in the previous section. The Kano model divides quality attributes into five categories:

1) *One-dimensional* attribute: If the technology presents this attribute characteristic, it means that the more (better) the technology provides, the higher the user satisfaction and *vice versa*.
2) *Attractive* attribute: the more (better) the technology of this type of attribute is provided, the higher the user satisfaction; if less is provided, the user satisfaction will not decrease.
3) *Must-be* attribute: users consider this type of technology mandatory and will cause great dissatisfaction if not provided.
4) *Indifferent* attribute: This refers to technologies that do not help increase user satisfaction regardless if provided or not.
5) *Reverse* attribute: The more techniques of this type of attribute are provided, the more dissatisfied users will be.

Conducting the Kano model requires an establishment of a questionnaire that consists of positive/functional and negative/dysfunctional questions. The respondent can answer a pair of questions in one of five different ways, "Like," "Must-be," "Neural," "Live with," and "Dislike," for each attribute of a GBT. The first question concerns the reaction of the customer if the GBT has that attribute (positive form); the second involves the reaction if the GBT does not have that attribute (negative form) (Xu & Juan, 2021). The questionnaire is then administered to various respondents, and each answer pair is aligned with the Kano evaluation table, as shown in Table 2, which can reveal each respondent's perception or preference toward attributes of the GBT.

In order to further quantify the Kano model, Matzler & Hinterhuber (1998) proposed the concept of Customer

TABLE 2 The kano evaluation table.

User requirements	Negative					
		Like	Must-be	Neutral	Live with	Dislike
Positive	Like	Q	A	A	A	O
	Must-be	R	I	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I	M
	Dislike	R	R	R	R	Q

Note: Q, A, R, I, O, and M denote "Questionable," "Attractive," "Reverse," "Indifferent," and must-be attributes, respectively.

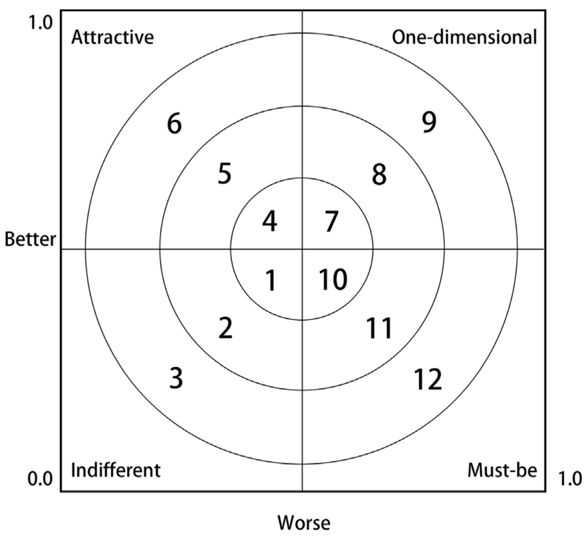

FIGURE 1
Distribution of CSC score.

Satisfaction Coefficient (CSC). The positive CSC (Better) ranges from 0 to 1, and the closer the value is to 1, the higher the impact of the technology's attributes on user satisfaction. Conversely, the closer the negative CSC (Worse) is to 1, the greater the effect on user dissatisfaction if the user's needs for the technology are not met. The Better and Worse coefficients can be calculated by the following equations:

$$\text{Better} = (A + O)/(A + O + M + I), \quad (1)$$

$$\text{Worse} = -(O + M)/(A + O + M + I). \quad (2)$$

The questionnaire based on the Kano model is used to specify the attribute of the GBTs. On the other hand, the CSC can further quantitatively analyze the weight score of these GBTs of users. Figure 1 presents the CSC weight score assignment schematic. The weight score of attributes in the CSC model is based on the rule of equidistant segmentation proposed by Juan et al. (2019) and Lu & Juan (2021), where the further the points in the same quadrant are from the center, the greater is their weight value.

In the four quadrants of CSC, the *Must-be* attribute in the lower right corner means users will be highly dissatisfied if the attribute is not provided; however, user satisfaction will not be increased if provided. The *Must-be* attributes should first be satisfied to reduce dissatisfaction, so the highest value of the preference score is 10–12. The upper right quadrant represents the *One-dimensional* attribute, which means that user satisfaction increases with the increase of the attribute provided. On the contrary, the less the attribute is provided, the more the satisfaction decreases. Compared to *Must-be* attribute, its importance is slightly lower. Hence, the GBTs that fall in this area are given moderately important scores (e.g., 7, 8, 9). In addition, the upper left quadrant belongs to the *Attractive* attribute, which means that the more technologies are provided in this area, the higher the satisfaction of users; meanwhile, the less it is provided, the less the satisfaction will be. The GBTs that fall in this area are given slightly important scores (e.g., 4, 5, 6). The last quadrant in the lower-left corner is an *Indifferent* attribute, which is generally chosen to be ignored. Due to the improvement of GB evaluation standards, a certain amount of technical support is needed to ensure compliance, so a minimum score of 1-3 is given in this category.

Zero-one integer programming

To test the market validity of the Kano model and CSC model decisions, this study uses Zero-one integer programming (ZOIP) approach to explore the relationship between the incremental cost and the user preference (CSC score) of GBTs for real development cases. ZOIP is a type of linear operation in management and operations research. It is used to solve programming with integer values of variables limited to 0 or 1 (Williams, 2002). To some extent, it has also been employed for solving multi-criteria problems. It is particularly effective for situations where projects are mutually exclusive and have interdependent technologies (Siu et al., 2016).

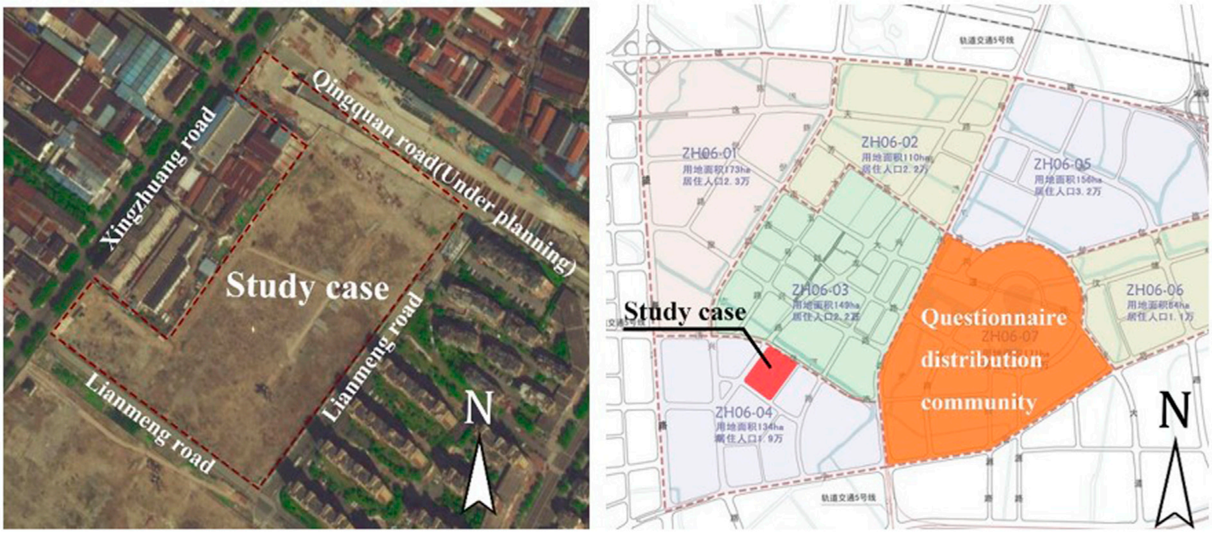

FIGURE 2
Environmental characteristics of the case study.

This study measures the relationship between incremental cost and user preference with GBTs from developers' perspectives (i.e., users' preference score for GBTs is considered with a fixed incremental cost budget). It is calculated as follows.

$$\text{Maximize } Z = \sum_{j=1}^{n} K_j X_j, \qquad (3)$$
$$\sum_{j=1}^{n} a_j X_j \le b, \quad X_j = 0 \text{ or } 1 \ (j = 1, 2, \ldots, n).$$

where K_j is the users' preference (CSC score) for GBT j; a_j is the incremental cost of GBT j; b is a limited budget of incremental costs; and X_j is the decision variable for GBT j.

Empirical research

Project debriefing

In order to test the effectiveness of this system framework, an upcoming residential development project in Ningbo, a city in the Yangtze River Delta, China, was selected as a case study, as shown in Figure 2. The site is located in the core area of the northern part of Ningbo Yongjiang Science and Technology Innovation Corridor, surrounded by several universities and technology industrial parks, which is the main residential area attracting the population to settle in Ningbo in the future. The east of the site is a new community built in recent years, with a population of 11,000 residents. The site covers an area of 52,700 square meters, with 1,000–1,100 residential units. With the growing foreign population in the Yangtze River Delta, developers are highly willing to provide residential units with 100 square meters to meet the rigid housing demand of the moving-in population.

In this study, 250 questionnaires based on the Kano model were distributed to the residents of the existing community on the east side of the site. They were all local residents willing to buy a housing unit in the next 5 years. Among all questionnaires, 171 were valid. Considering that most respondents were not professional enough to know about GBTs, each question was explained and described to enhance their understanding. In addition, among the 21 technologies, three (#19, #20, and #21) were removed from the questionnaire because they were more related to professional construction technologies and had a slight relationship with users' experience. Therefore, only the first 18 items were selected for study in the follow-up questionnaire.

Results of the Kano model and customer satisfaction coefficient

Furthermore, a reliability analysis was conducted for the Kano model forward/reverse questions using SPSS, respectively, to ensure the rigor of the study. The standardized Cronbach's α coefficient for the positive questions was 0.831, while that for negative questions was 0.905. The results indicate that the quality of data reliability passed the test and can be used for further research.

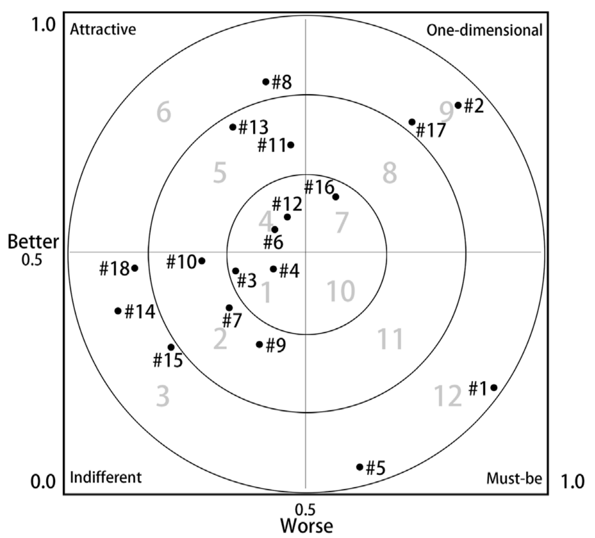

FIGURE 3
CSC satisfaction matrix of GBTs.

The questionnaire results were calculated using the Kano model and CSC, as shown in Figure 3. The user preference (CSC score) is shown in Table 3. Further, the study conducted interviews on this result and obtained some findings.

1) Among the top five items, the first three items, #1, #5, and #2, were closely related to the quality of the indoor environment used by users. As for Item #17, respondents reported that Ningbo has a lot of rainfall, especially in the summer typhoon weather, where waterlogging and flooding occur, so permeable pavement was necessary. Item #16 was also closely related to the quality of the outdoor environment for users. It is apparent that the first five items are directly related to occupants' life experience, and the rest of the GBTs mostly favor energy-saving effects.
2) Developers did not expect that the "#4 New air system" and "#9 Low-E center louvered glass" also belong to indoor environmental quality improvers, which incurred high costs. Hence, it fell into the quality of *Indifference.* This result may be related to the local climate and living culture. For instance, most households believe that Ningbo is windy in all seasons, and opening windows for ventilation might be more efficient than the new air system for air exchange. In addition, the Low-E center louvered glass is a new technology based on the traditional Low-E glass. Developers have employed this technology in recent years to improve the effect of shading and insulation. However, many users found that the Low-E center louver glass was aesthetically low, and the device controlling the louvers was difficult to operate and repair, resulting in more confusion for users to adopt the technology.

Results of zero-one integer programming analysis

Based on the user preference evaluation of the 18 GBTs provided by the CSC results, the research team invited experts

TABLE 3 User preference (CSC score) of GBTs.

Ranks	GBTs		CSC score	Weight score
1	#1	Advanced Environmental Durable Decoration	12	1.000
2	#5	Accessible design	12	1.000
3	#2	High performance sound insulation materials	9	0.750
4	#17	Permeable pavement and green stormwater infrastructure	9	0.750
5	#16	Community three-dimensional greening	7	0.583
6	#8	Energy-saving air conditioning system	6	0.500
7	#11	High-performance envelope (exterior wall insulation)	5	0.417
8	#13	Efficient water-saving sanitary ware	5	0.417
9	#6	Energy consumption monitoring system	4	0.333
10	#12	Energy-saving electric lights, elevators, and other electrical equipment	4	0.333
11	#14	Water-saving green irrigation technology	3	0.250
12	#15	Comprehensive recycling of rainwater	3	0.250
13	#18	Green Roof	3	0.250
14	#7	Intelligent Air Monitoring System	2	0.167
15	#9	Low-E center louvered glass	2	0.167
16	#10	High-efficiency heat and cold source system (solar water heater)	2	0.167
17	#3	Adjustable external shading	1	0.083
18	#4	Air purification new air system	1	0.083

TABLE 4 The incremental cost information of GBTs.

GBTs		Interpretation	Unit incremental cost (CNY)	Incremental cost per household with 100 m^2 (CNY)
#1	Advanced Environmental Durable Decoration	Comparison between pure solid wood flooring and ordinary multi-layer laminate	80/m^2	8,000
#2	High performance sound insulation materials	Adding acoustic felt	50/m^2	5,000
#3	Adjustable external shading	Comparison between the installation of adjustable external shading and no installation	25/m^2	2,500
#4	A new air system for air purification	Comparison between installing one set per household and not installing	100/m^2	10,000
#5	Accessible design	Anti-slip rubber strips, handrails, and barrier-free ramps	5/m^2	500
#6	Energy consumption monitoring system	Smart electricity and water meters, one set per household	4/m^2	400
#7	Intelligent Air Monitoring System	Underground garage CO monitoring, one set per 40 households combined	5/m^2	500
#8	Energy-saving air conditioning system	Comparison of primary and tertiary energy efficiency, 1.5 hp per unit, three units in a household	24/m^2	2,400
#9	Low-E center louvered glass	The incremental cost of 600 RMB per square meter of glass	96/m^2	9,600
#10	High-efficiency heat and cold source system (solar water heater)	Solar water heater vs. wall-hung water heater	12/m^2	1,200
#11	High-performance envelope (exterior wall insulation)	High-efficiency insulation facade versus ordinary insulation facade materials	50/m^2	5,000
#12	Energy-saving light bulbs, elevators, and other electrical equipment	Energy-saving electric lights compared with ordinary light bulbs, calculated by 10 per household; energy-saving elevators are calculated by one staircase and 20 floors	10/m^2	1,000
#13	Efficient water-saving sanitary ware	Comparison of Class I water-saving sanitary ware and ordinary water-saving sanitary ware, calculated by two per household	4/m^2	400
#14	Water-saving green irrigation technology	Water-saving irrigation versus normal irrigation for the whole plot green area calculation	10/m^2	1,000
#15	Comprehensive recycling of rainwater	Comparison with no rainwater recycling device	5/m^2	500
#16	Community multilevel greening	Compare the average cost of multilevel greening and normal greening	40/m^2	4,000
#17	Permeable pavement and green stormwater infrastructure	Permeable pavement vs. impermeable pavement	5/m^2	500
#18	Green Roof	Comparison of green roofs and non-roofs, based on a 20-story building	25/m^2	2,500
Total		—	—	55,000

and developers to explore the relationship between technology cost and user preference. In particular, four long-time residential architects (two of whom are working on this project), three university architecture academics, and two developers were invited to discuss and specify the incremental cost per unit area (m^2) of each GBT, as shown in Table 4.

In an open-ended interview, the research team asked the following questions and invited developers and architects to conduct in-depth interviews.

- Which part is your biggest difficulty in choosing GBTs?
- Which indicators will be assessed in the selection of GBTs?
- Will users' acceptance or marketability be considered to adopt GBTs in the projects?
- Are you sensitive to the cost of different GBTs?

In the course of the interviews, this study found that deciding on the selection of GBTs is a critical and difficult issue for respondents. For example, they could not judge what investments were made to achieve the GB certification level within a limited budget and increase owner satisfaction. In addition, the most critical consideration for their choice of GBTs is cost and owner's acceptance. If the cost is too high, market acceptance or demand is low, developers naturally have no incentive to adopt these GBTs. Therefore, calculating the incremental cost per unit of GBTs and the user preference scores through ZOIP will help developers reasonably select optimal technologies combined with higher user satisfaction at the expected costs.

For the developer in this project, the incremental cost of GBT is expected to be controlled at CNY 250 per square meter (the

TABLE 5 ZOIP operations with a budget of 25,000 RMB.

GBTs	CSC score	CSC weight score	Incremental costs (CNY)	Result of ZOIP*
#1	12	1.00	8,000	1
#2	9	0.75	5000	1
#3	1	0.08	2,500	0
#4	1	0.08	10,000	0
#5	12	1.00	500	1
#6	4	0.33	400	1
#7	2	0.17	500	1
#8	6	0.50	2,400	1
#9	2	0.17	9,600	0
#10	2	0.17	1,200	0
#11	5	0.42	5,000	0
#12	4	0.33	1,000	1
#13	5	0.42	400	1
#14	3	0.25	1,000	1
#15	3	0.25	500	1
#16	7	0.58	4,000	1
#17	9	0.75	500	1
#18	3	0.25	2,500	0

Note: "1" means the adoption of the technology; "0" means the non-adoption of the technology.

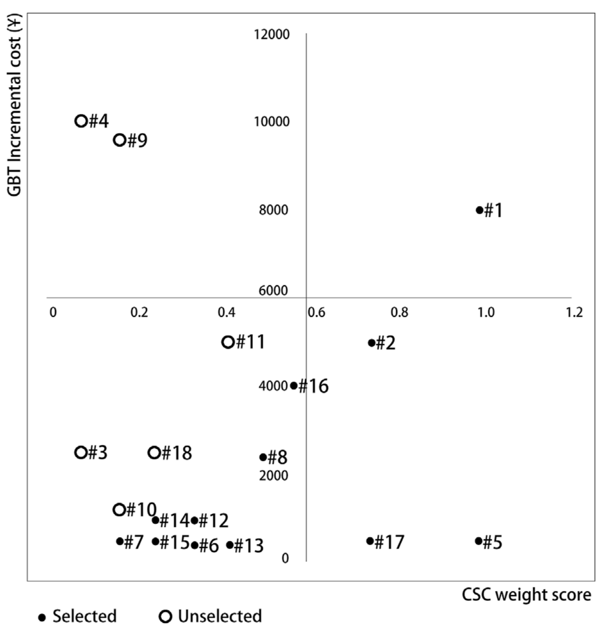

FIGURE 4
Score-cost analysis diagram of GBTs.

total budget for a unit is CNY 25,000) to meet the high standard of GB certification. As shown in Table 5, the result of the optimal decision-making revealed that the total CSC weight score could reach 6.33, and the actual cost of selected GBTs would be CNY 24,200. These technologies were not selected mainly because of their poor performance in terms of cost-effectiveness. This study further formulated strategies for evaluating the adoption of GBTs. The result is shown in Figure 4:

- Low-cost and high-scoring GBTs should be prioritized, such as "#5 Accessible design," "#17 Permeable pavement and green stormwater infrastructure", and "#2 High-performance sound insulation materials", implying that the community residents generally had a high demand for the use of outdoor environments.
- High-cost and low-scoring GBTs, such as "#4 Air purification new air system" and "#9 Low-E center louvered glass," will not be selected. In other words, if GBTs with high costs fail to make users aware of their value, it will also reduce the market acceptance of these GBTs.
- GBTs with high cost but also with high scores have a high chance of adoption, such as "#1 Advanced environmental durable decoration" and "#16 Community three-dimensional greening", implying that users are willing to pay good GBTs with functionality or value, even if the cost was high.
- Low-cost and low-scoring GBTs still have a chance to be adopted, such as "#7 Intelligent Air Monitoring System", "#8 Energy-saving air conditioning system," "#12 Energy-saving electric lights, elevators, and other electrical

TABLE 6 Sensitivity analysis of budget and score changes.

Budget (*B*, CNY)	*X* =(*B*-baseline budget)/baseline budget	Total weight score (*S*)	*Y* =(*S*-baseline score)/baseline score
32,500	30%	7.00	10.53%
31,250	25%	6.92	9.21%
30,000	20%	6.75	6.58%
28,750	15%	6.75	6.58%
27,500	10%	6.58	3.95%
26,250	5%	6.50	2.63%
25,000	0%	6.33	0.00%
23,750	−5%	6.16	−2.63%
22,500	−10%	5.92	−6.58%
21,250	−15%	5.75	−9.21%
20,000	−20%	5.75	−9.21%
18,750	−25%	5.58	−11.84%
17,500	−30%	5.5	−13.16%

equipment," "#13 Efficient water-saving sanitary ware," "#14 Water-saving green irrigation technology", and "#15 Comprehensive recycling of rainwater." This finding may have resulted from the fact that there was still room for low-cost GBTs to be included in the "package" with budget slack.

Discussion

Sensitivity analysis of budget allocation

In order to verify the benefits of budget allocation, this study conducted a sensitivity analysis using ZOIP to explore the changes in user preference scores under different budget conditions. The result can be utilized as a reference for budget planning for housing developers.

The sensitivity analysis is a method that measures how the impact of uncertainties of one or more input variables can lead to uncertainties on the output variables (Pichery, 2014). Firstly, the input variable of the budget (X, maximum increase up to 30%, CNY 32,500; a minimum decrease of 30%, CNY 17,500) was determined step by step with a budget base of CNY 25,000 per household (100 square meters) in 5% increments. Secondly, ZOIP optimization was performed under different budget conditions to obtain the total CSC weight scores (output variable, Y). Lastly, the sensitivity of the analysis was conducted by plotting the relationship between budget and score changes, as shown in Table 6 and Figure 5. Sensitivity analysis is performed using the following formula: X = budget difference/baseline budget, and Y = score difference/baseline score, at ± 30% level in the changes.

As presented in Figure 5, if the developer increased the budget, more GBTs could be selected, and the score could also be higher. When the budget changes were between −15% and 15%, the overall line slope was large, indicating that increasing the budget investment in this range can effectively improve the score (user satisfaction). Outside the range, when the developer increased the budget by more than 15% (CNY 28,750), the score increased, and the slope of the score also decreased, indicating that despite the developer investing more money, the increase in user satisfaction was not significant. On the contrary, if the developer's budget were reduced by 15%, user satisfaction would not decrease significantly.

The sensitivity analysis results indicate that if the developer can control the budget of GBTs adoption for each housing unit between CNY 21,250 and CNY 28,750, the company can acquire the optimal GBTs adoption solutions with acceptable user satisfaction. Furthermore, the results of this study can provide developers with a more effective and flexible budget allocation mechanism, thus reducing the waste of costs, technology, and human resources.

Comparison of research results with existing studies

The results showed that the top five GBTs were directly related to indoor and outdoor environmental quality. Compared with energy-saving technologies, users were more willing to pay for the green premium of comfort, health, and productivity brought by GBTs. Although this conclusion differed from the emphasis on energy conservation research in developed countries, it seemed more consistent with the past research on GB in China. For instance, Hu et al. (2014) also conducted a

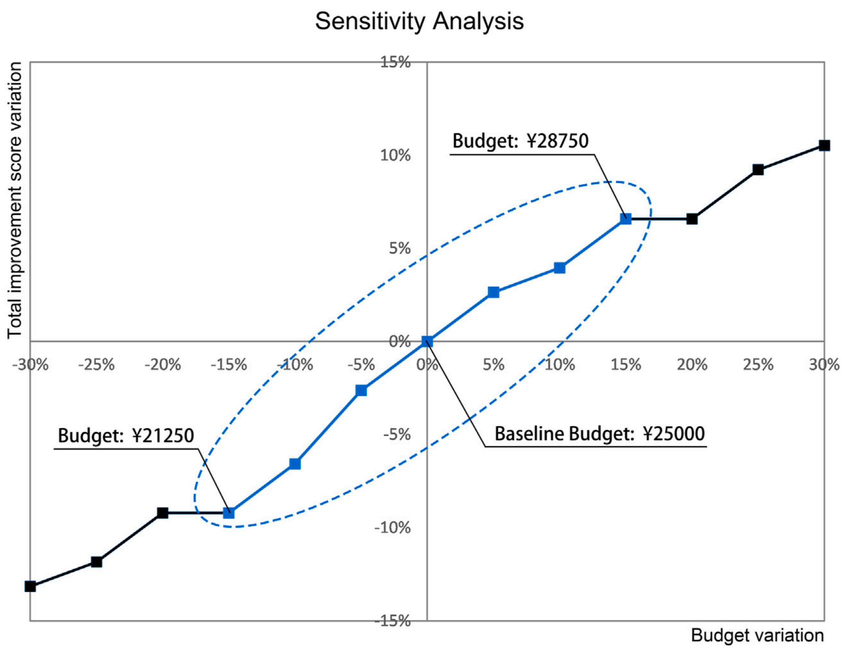

FIGURE 5
Results of sensitivity analysis.

survey on GB housing in Nanjing, China and found that residents considered healthy and environmentally friendly building materials the most important. This finding was also in accordance with the "#1 Advanced Environmental durable decoration" (ranked first) in this study. Similarly, Zhang et al. (2020) carried out a survey on green hotels in Beijing, China and found that customers had the highest willingness to pay for GB's indoor environmental quality. The study of Kyu-in and Dong-woo (2011) on residential users of green buildings in South Korea found that residents paid much attention to non-toxic materials and the sound-absorbing performance of buildings, which was consistent with the top two results (#1 and #2) in this study.

Notably, the "#5 Accessible design" ranked second among the CSC scores, probably because many respondents believed barrier-free design is necessary for senior housing, in addition to the provisions of building regulations. This result may have a certain relationship with the aging of Chinese society and also reflects the public's increasing attention to the fairness of use. Another interesting finding was that "#17 Permeable pavement and green stormwater Infrastructure" ranked fourth. Interviews revealed that residents were concerned about the increasing incidence of extreme rainstorms causing urban waterlogging. In particular, under the influence of extreme global weather, the frequent heavy rains and urban waterlogging in many of China's megacities have drawn great attention from the Chinese government. In 2015, China launched the "Sponge City Plan" to continuously promote and strengthen the construction of urban groundwater permeability and green infrastructure. Its promotion and publicity have directly strengthened public awareness and residents' attention.

However, "#9 Low-E center louvered glass" and "#4 Air purification new air system," which have been widely promoted in recent years, were not popular among users. Although numerous studies have shown that households were highly concerned about clean air and temperature, the high cost may affect their willingness to adopt. This inclination might also be related to the humid and windy climate of the local Ningbo city under investigation. Some residents who have used the fresh air system believe that the natural ventilation of the building is better than the fresh air system. For instance, Tong et al. (2016) conducted a study on natural ventilation in 35 cities in China. They found that the natural ventilation conditions in Ningbo have a large energy-saving potential, which may explain why the respondents were more accustomed to natural ventilation.

According to the score-cost analysis diagram of GBTs in Figure 4, GBTs with low cost and high preference, high-cost and low-cost comfort, and low energy-saving should be adopted preferentially. This result was fully in line with the concept of differentiation strategy in the competitive strategy proposed by Porter (1985), which means that low-cost and high-benefit strategies should be given priority, and high-cost strategies need to consider the market value. In addition, users must also decide their adoption priority order. It is worth noting that between basic health and comfort and energy-saving, people usually pay more attention to health and comfort. However, with the mandatory promotion of China's GB standards, the public's awareness of energy conservation is increasing, maintaining the opportunity to increase the adoption of energy-efficient GBTs in the future.

Conclusion

In the next few years, China is expected to have 1 billion square meters of new residential floor areas per year. Facing emerging environmental issues such as global warming and energy consumption, the Chinese government continues to raise energy efficiency standards and requirements for the construction industry. GB certification for residential buildings has become an important guarantee for achieving carbon peaking and carbon-neutral targets in most regions of China. Thus, to meet China's GB certification standards, developers blindly pile on all kinds of GBTs to obtain higher GB scores. However, occupants' experience regarding GBTs benefits is often ignored—occupants often change the designs after moving in. This process has resulted in a lot of waste of money, materials, and manpower, causing unnecessary losses to developers and users.

The novelty and three main contributions of this study are described below. First, we construct a method based on the Kano model and CSC to effectively mine user needs, and apply it to the selection of GBTs, which can help developers and architects understand users' preferences for GBTs. The results showed that occupants were interested in technologies that can directly improve the quality of indoor and outdoor space use, and they were more concerned about adopting energy-saving technologies with acceptable incremental costs. Second, we develop a cost-benefit decision-making model based on ZOIP, which can provide a systematic framework for developers to effectively control the incremental costs and benefits of GBs. Last and foremost, developers can pay more attention to users' perceptions and evaluations of the GBTs in the pre-design stage while making delivery more attractive and cost-benefit housing products to improve their competitive advantages in housing markets; the government can also use this method to encourage developers to launch more GB projects in an efficient way after considering building regulations, market and technical aspects.

It is also worth noting that there are still some limitations in the practical application of this study. First, this study focused on greenhouses in China's Yangtze River Delta region, which is unique and whose approach does not necessarily apply to the pre-design simulation analysis of greenhouses in different regions. The implementation of GB and the selection of GBTs are highly localized. Although this study uses this region as a case study, the proposed decision model might be adjusted and applicable according to different local standards, construction conditions, and climate characteristics in different regions. More cases can be selected in the future to verify the decision-making model proposed in this study. Second, this study focused on occupants, developers, and designers, not considering other stakeholders, such as government managers and property managers, who might also affect the success of the GB projects. Furthermore, about 55% cost savings can be achieved in GB design through a reasonable combination of active technology and passive design (Ahmad et al., 2016). However, considering that passive design (e.g., ventilation, orientation, lighting, and form of the building) is mostly dependent on the designers' ability and tacit knowledge, it is difficult to measure the cost and benefits of passive design quantitatively. Therefore, in the future, it might be possible to incorporate passive technologies into the proposed system to develop a more thorough system Si et al., 2016, Wang et al., 2005.

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

HL contributed to investigation, data curation, validation, and writing-original draft preparation. Y-KJ contributed to the conception, methodology and design of the study, as well as writing-original draft preparation, and review and editing. 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.

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Achieving carbon neutrality in China: Legal and policy perspectives

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China has committed to achieve carbon neutrality by 2060. However, this task is considerably difficult. To meet its carbon neutrality commitments, China will rely on a range of policies and laws. By analyzing policies and laws issued at the central and local levels in China from 2019 to the present, we assessed how the Chinese government will achieve its carbon neutrality targets by breaking them down. The results of this study showed that: 1) Carbon neutrality targets are translated into indicators such as energy consumption per unit of GDP, carbon dioxide emissions per unit of GDP, non-fossil energy consumption ratio, forest cover, and forest stock; 2) The focus of policy and law-making is on the role of the government rather than the carbon market; 3) The central government tends to promote and guide low-carbon development through specific actions; 4) Local policy and law-making is less proactive and is influenced by localism; 5) Overall, China's carbon neutrality policies and laws are characterized by comprehensive coverage, with emphasis on the rational use of executive power and the development of low-carbon-related technologies; and 6) The existing policies and laws remain unclear, with low levels of legislation and insufficient public participation. This paper puts forward some suggestions on the introduction of the climate change law, the promotion of citizen participation in policy-making and implementation, and the establishment of a public interest litigation system on climate change.

KEYWORDS

carbon neutralization, carbon peak, policy and law, implementation path, climate change law

1 Introduction

Climate change is a global issue increasingly affecting human health, socio-economic development, population migration, food security, and terrestrial and marine ecosystems. Due to the increasing number of extreme climate disasters reported by the media in recent years, countries have started to set specific targets to decrease carbon emissions. The European Union (EU)'s Green Deal, launched in 2020, aims to make the EU climate-neutral by 2050[1]. As the world's largest emitter of greenhouse gases, China has taken

1 European Commission (2019), The European Green Deal. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640&qid=1660118669836.

action against climate change, aiming to peak carbon emissions by 2030 and become carbon neutral by 2060 (Mallapaty, 2020). This is a key step for China to address global climate change and contribute to the global environmental governance system. In September 2021, the Chinese government put forward the basic approach to achieve this goal, based on the aim to extend the principle of overall planning to the whole country, the strengthening of top-level design based on a national strategy, giving full play to institutional advantages, and improving existing laws and regulations. Therefore, the formulation of appropriate laws and policies to give full play to institutional advantages is an important means for China to achieve carbon neutrality.

Since the reform and opening up, China's economy has experienced a rapid development, accompanied by an increase in environmental pollution. To protect the environment, more than 30 laws have been enacted and implemented, including the "Environmental Protection Law," the "Air Pollution Prevention Law", the "Clean Promotion Law", the "Coal Law", and the "Mineral Resources Law". However, China's environmental legislation still faces a series of challenges and problems, including the lack of full implementation of the concept of sustainable development, as well as gaps and inconsistencies between laws and regulations, unclear responsibilities, an imperfect system design, unbalanced rights and obligations, an implementation being significantly affected by the GDP, the lack of applicability of legal content, and difficulties in public participation (Mu et al., 2014). These problems also apply to the issue of carbon peaking and carbon neutrality, in addition to a whole series of other legal problems in relation to China's carbon emissions. In fact, at the macro level, there is a lack of a master plan for scientific, low-carbon development, and the existing market-oriented management tools are still immature, which makes it difficult to coordinate with the administrative management tools. At the micro level, the legislation regulating each specific production sector is still insufficient (Han, 2014). This reflects the fact that the supply of public goods in China depends on the institutional inertia of administrative power, which limits the role of market-based tools in carbon emission reduction, and that the relevant administrative system has not been established. Faced with the arduous task of carbon emissions reduction, legislation is bound to continue to strengthen the executive power. Therefore, if China wants to achieve its carbon peak and carbon neutrality as soon as possible, it must have a complete legal framework for carbon management. On the one hand, the efficiency of emissions per unit of carbon through the carbon market should be improved. On the other hand, a rational management system should be established including energy transformation, energy-saving technology, carbon capture and utilization technology, and carbon sequestration technology, among others (Wang et al., 2021).

The aim of this study was to answer the following three questions: 1) What is the level of implementation of different carbon neutrality policy tools (especially market and government policy tools) in China's legislation? 2) What are the administrative tools that China has adopted to achieve carbon neutrality, and what are their characteristics? and 3) What are the characteristics of China's carbon neutrality policies and laws, and how should they be further improved? In order to answer these three questions reliably, this study divided carbon neutrality policies into two types: market-based incentives and government regulation, which represent different paths to achieve carbon emission reduction. Then, an assessment was conducted of the policies and laws issued after the carbon peak and carbon neutrality targets were put forward in China. More in detail, this study explored the path of China's carbon neutrality goal by analyzing the text of China's national and local legislation issued from 2019 to 2022, allowing to investigate the existing problems across different paths, and to identify feasible ways to improve the role of the government.

The theoretical and practical contributions of this study are as follows: 1) At a theoretical level, this study analyzed the differences between central and local governments in implementing carbon neutrality requirements, as well as the development of policies and laws; 2) It shed light on the perspective and mechanisms of action of carbon neutrality-related laws and policies, while at the same time it further analyzed the possible defects of such laws and policies; 3) It put forward suggestions to establish a more effective policy and legal system for carbon neutrality. This study provided a valuable literature review and research ideas to rationalize the role of the government in the achievement of carbon neutrality. At the same time, it also provided a reference to establish a more effective policy and legal system for carbon neutrality.

2 Literature review

Traditional environmental laws deter enterprises and individuals from harming the environment by employing fines, closure and rectification, and treatment of pollution (Li and Wu, 2017). However, carbon-neutral environmental governance, which aims to provide a public good, i.e., to stabilize the level of greenhouse gases in the atmosphere, limits the effectiveness of deterrent legislation. Therefore, taxation and subsidies have become widely used tools to curb the emissions of high carbon-emitting industries through taxation, and to encourage the development of low-carbon industries. However, these two tools do not necessarily work as intended. In the 1990s, the carbon tax was the first choice for European countries to reduce emissions. Although it was promoted in several countries and regions, its shortcomings have also been evident. In fact, as the carbon tax entails an increase in the price of fossil fuels, including gasoline, diesel, and natural gas, social and public opposition to the tax emerged in the early days. In addition, the definition of carbon tax categories and tax rates is complicated. While a low-level tax rate will not reduce carbon emissions, a high-level tax rate will increase the burden on businesses, and then affect the international competitiveness of domestic industries (Hoel, 1996). On the contrary, a carbon tax on goods would force other countries to take steps to reduce emissions. The EU's Green Deal specifies the EU's Carbon Border Adjustment Mechanism, and the EU levy on the carbon emissions of some imported goods covers most EU countries (Ortega-Gil et al., 2021). Subsidy systems are widely used in the field of environmental protection, especially in the fields of research and development of environmental protection technology, energy conservation, and promotion of new energy products. However, as a financial means for the government to intervene in the market, the breadth and depth of implementation of a subsidy policy are constrained by the government's financial capacity and rigid budget. Therefore, the implementation of a subsidy system is often only applicable to a specific scope, and there are time constraints (Wang and Tao, 2018).

In order to achieve emission reduction targets, the EU has imposed relatively strict emission standards on some industries such as the automotive industry (Krämer 2020). Although existing climate policy measures will likely reduce emissions by more than 40% by 2030 in the wake of the COVID-19 pandemic, this will not be enough to meet the targets set by the Paris agreement (Meles et al., 2020). Therefore, in December 2020 the leaders of the 27 EU Member States reached a consensus on a revised emission reduction plan, agreeing to reduce the EU's greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. On 14 July 2021, the European Commission announced a package plan called "Fit for 55" ("Carbon Reduction 55"), which covers climate, energy, transportation, and societal aspects. This plan proposes to expand the EU carbon trading market, stop the sale of fossil fuel-based vehicles, expand the share of renewable energy, and establish a carbon border tax and other new laws, thereby providing a substantive set of actions to achieve the set goal.

Using carbon markets to reduce carbon emissions is a common practice in countries around the world. Drawing on the foreign experience of carbon trading, in 2013 China officially launched a pilot project on carbon trading in seven provinces and cities; also, other provinces and municipalities launched their own carbon trading schemes, and in December 2017 the establishment of a unified national carbon trading market was announced. However, the carbon trading market is currently in its infancy, and the price of carbon trading is volatile. In several areas, the allocation of carbon trading quotas, business models, carbon emission reduction statistics, and other mechanisms need to be further explored and depend on the effective formulation of policies and laws (Zou et al., 2021). Recently, the price of carbon allowances under the EU's Emissions Trading System (ETS) has been rising from \$30 a tonne in 2021 to more than \$90 a tonne in 2022. However, in a moment when the price of carbon hit record highs and nearly broke the threshold of \$100, the conflict between Russia and Ukraine broke out, triggering financial market turmoil and risk aversion. Investors began to sell carbon assets in order to cut their losses; the price of carbon halved in a few days and plunged to a low of 55 Euros on 2 March 2022. This suggests that even the more regulated EU carbon market suffers from excessive price volatility. At present, the "Carbon emissions trading management measures (trial implementation)" is the only national law in place for specific carbon emissions management in China. Although it includes detailed provisions, the scope of action is small, the subject of regulation is single, the legal status is low, and its role in the achievement of the national "double carbon" target is limited (Hao and Yang, 2022). Unstable carbon prices will undoubtedly hinder the role of the carbon market, and the incomplete regulatory system for carbon financial products will magnify the shortcomings of the rules of the carbon market. Carbon financial products should be able to transfer environmental risks through the market and maximize the efficiency of resource allocation (Labatt and White, 2006). However, the development of green finance in China still faces multiple difficulties; in fact, the policies and standards are unclear, product innovation is not timely, and the international cooperation is not extensive (Zhou, 2022).

China's energy structure is highly dependent on coal, which is used to produce more than half of all electricity; more than 70% of China's power plants are coal-fired, generating 44% of the country's carbon emissions. Therefore, in addition to the market-based reform of the electricity sector, there is a need to adopt a series of policies such as the diversification of power sources, the clean and efficient transformation of coal-fired power plants, the setting of ultra-low emission standards, and the introduction of subsidy policies to support electricity prices in order to promote low-carbon energy production (Zhang et al., 2020). In addition, China's current efforts to reduce emissions have much in common with those of other countries in terms of energy efficiency, development of electric vehicles, and increased afforestation; however, limited by the current level of economic development and resource endowments, China faces huge professional challenges in reducing industrial carbon emissions and the supply of coal and coal power (Zhang et al., 2022) These factors demonstrate that legislation emphasizing the full use of market-based tools is not enough, and that total energy consumption control and industrial structure optimization are the main ways to reduce carbon emissions (Wang et al., 2021). In addition to continuing to improve the carbon market-related legal system, the improvement of other relevant administrative legal systems should also become another focus of research.

Scientific and technological innovation plays an important role in carbon emission reduction. It is generally believed that the

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development and popularization of long-term, high-cost new technologies rely heavily on public policy support (Geels et al., 2020). In relation to technological innovation, the Porter hypothesis argues that proper environmental regulation can stimulate innovation, increase productivity, and ultimately offset the costs of environmental regulation (Porter and Linde 1995). This hypothesis, however, has not been proven (Wei et al., 2021). Therefore, in addition to regulation, China has adopted a centralized and locally implemented approach for the allocation of environmental subsidies in terms of economic mechanisms that provide incentives for environmental protection. Previous research showed that such subsidies encourage companies to innovate in environmental protection to a certain extent (Klette et al., 2000). In addition, government procurement can stimulate, create, and expand the market demand for environmentally friendly products and services, which is conducive to the improvement of environmental issues and to the achievement of the overall goal of sustainable development (Georghiou et al., 2014). Legal and institutional government action can make an important contribution to carbon neutrality; however, there is still insufficient research on how to systematically promote emissions reduction through improved policies and laws.

3 Materials and methods

In order to further improve the market rules, the Chinese Ministry of Ecology and Environment has issued the "Management Measures for Carbon Emissions Trading (trial implementation)", the "Rules for the Management of Carbon Emissions Registration (trial implementation)", the "Rules for the Management of Carbon Emissions Trading (trial implementation)", and the "Rules for the Management of Carbon Emissions Settlement (trial implementation)", establishing a legal and policy system for the effective operation of the national carbon emission trading market. However, improving the trading rules and the regulatory system will be a long and complex process, requiring patient trial and error. In addition to improving the rules of the carbon market, China has enacted several policies and laws to achieve carbon neutrality, laying the foundation for a specific climate change law in the future. By searching the keywords "carbon neutrality" in the title, we collected all the central and local laws and policies that have been issued; the content of these documents are listed in Table or Appendix. As of October 2022, there are 14 central regulations and regulations of national organizations that are subject to substantive restrictions. Inside the framework provided by the central legislation, local governments can choose their priorities according to the development needs of their regions and formulate corresponding local ordinances and policies. The same keyword search yielded 79 local regulations and policy documents (as shown in Supplementary Material); further analysis of these policies and legal texts revealed the priorities of local governments in implementing carbon neutrality. In September 2020, the President of the People's Republic of China announced at the 75th United Nations General Assembly that "China's carbon dioxide emissions will strive to reach the peak by 2030 and strive to achieve carbon neutrality by 2060". The goal of low-carbon development in China has, thus, become clear. Before that, in May 2019 the Chinese Ministry of Ecology and Environment issued the "Carbon Neutralization Implementation Guide for Large Scale Activities (trial implementation)" to standardize large-scale activities. Therefore, this study analyzed the main central and local policies and laws on carbon neutrality issued in China after 2019 through the literature analysis method.

4 Results

4.1 Carbon neutrality targets and paths in China's policies and laws

4.1.1 Carbon neutrality targets in China's policies and laws

The "Central Committee of the Communist Party of China and the State Council's Opinions on Fully, Accurately, and Comprehensively Implementing the New Development Concept and Achieving Peak Carbon and Carbon Neutrality", issued in 2021, concretizes the targets for carbon neutrality into several indicators, such as energy consumption per unit of GDP, carbon dioxide emissions per unit of GDP, non-fossil energy consumption ratio, forest coverage, and forest volume, and sets the specific objectives for the various stages of implementation. It can be found that the current carbon intensity reduction target cannot be replaced by total carbon emission control until a complete carbon emission market system is established. Internationally, the more authoritative and widely recognized definition of greenhouse gases was proposed by the United Nations Framework Convention on Climate Change (UNFCCC). Article 1, paragraph 5 of the UNFCCC defines greenhouse gases as "natural and man-made gaseous substances in the atmosphere that absorb and reemit infrared radiation"[2]. Specifically, the emissions of six greenhouse gases, namely carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons, and tetrafluoromethane, should be controlled and limited[3]. On the eve of the

2 United Nations. (1992) United Nations Framework Convention on Climate Change. Available at: https://unfccc.int/resource/docs/convkp/conveng.pdf.

3 Specifically, emissions of the following six greenhouse gases shall be controlled and restricted: carbon dioxide (CO_2), methane (CH_4), nitrous oxide(N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFC), and perfluorocarbon (PFC).

TABLE 1 Differences between the carbon peak legislation of China and the EU.

	China's carbon peak action plan by 2030	European union climate law
Subject matter and scope	Establish the guiding ideology and action principle	Building a legal framework
Climate-neutrality objective by 2030	Flexible multiple objectives	Rigid single objective
Provisions on science and technology	Strengthen the layout and promotion of basic research	Set up of the European Scientific Advisory Board
Adaptation to climate change	Promoting green and low-carbon development in the region from a practical perspective	Special concern towards the most vulnerable and impacted populations and sectors
Assessment of Union progress and measures	Strict supervision and assessment	Review and evaluation every 5 years and adoption of necessary measures
Public participation	No rules	Rules have been established

Copenhagen Climate Change Conference in 2009, to achieve a constructive outcome in international climate negotiations, the State Council of China formally announced the country's greenhouse gas emission control target of reducing carbon dioxide emissions per unit GDP by 2020 by 40%–45% compared to 2005 levels. This is the first time that China has committed itself in front of the international community with a relatively clear quantified emission reduction target. To fulfill the international commitments on greenhouse gas control, the carbon dioxide emission intensity per unit of GDP was set as a binding index in the 12th and 13th Five-year plans. However, in the policy documents, after the setting of the carbon neutrality target, it can be found that the energy structure transition, forest cover, and forest stock have also been included in the broad emission reduction targets.

4.1.2 The path to carbon neutrality in China's policies and laws

Unlike the EU, which relies more on framework laws to achieve emissions reduction, China relies on achieving its emissions reduction goals through bureaucracy under the guidance of some principles (shown in Table 1). These principles are flexible to some extent; however, once the indicators are determined, their implementation is rigid. After 2019, regulations and policy documents with the names "peak carbon" or "carbon neutrality" broke down these overall goals to articulate how China will achieve carbon neutrality (as shown in Table 2). To achieve this objective, China attaches great importance to the use of financial instruments, preferring subsidies rather than taxes, thereby stimulating companies to reduce their emissions through innovative technologies. Due to the strong government guidance, China is trying to set up a low-carbon standard system to guide enterprises and society to achieve green and low-carbon development; moreover, it has also imposed stricter requirements on key sectors such as energy, state-owned enterprises, new infrastructure, eco-industrial parks zones, and transportation. In these areas, relevant standard systems are also beginning to be formulated at the level of the central government. To ensure the reorganization of human resources, the Ministry of Education of China issued a special document to provide scientific and technological support and personnel security for the achievement of carbon peak and carbon neutrality targets. In general, these policies and laws have a common feature of promoting and guiding the whole society to achieve low-carbon development through government actions.

Because the interests of the central government and the local government are different, central environmental policies are not fully implemented in some places. As a result, the environment has continued to deteriorate, affecting people's life, especially after 2010. By emphasizing the importance of the central authority and strengthening the implementation of the central environmental policy, the implementation of these policies can be significantly improved. However, strict environmental protection will hinder local development. When the "Legislative Law" was amended in 2015, the local government was given the power to formulate regulations in the field of environmental protection. Thus, a relatively ideal governance relationship initially formed, and the central government and the local governments should realize a cooperative environmental governance mechanism through the division of labor and cooperation, whereby the central government will not be responsible for all legislation.

From the 79 local policies and laws analyzed, we can see that the role of local governments in the process of achieving carbon neutrality is still relatively limited. In fact, 26.58% of these policies and laws emphasize the comprehensive legislation of the central government, while 35.44% emphasize the development of science and technology for emission reduction in the region (as shown in Table 3). Moreover, the majority of the comprehensive policies and laws are not clear enough. Only a few provinces, such as Shanghai, Jiangxi, and Qinghai, have defined their development indicators as e.g., non-fossil energy consumption ratio, forest coverage rate, and forest volume, while most provinces have not set specific development goals. There is little appetite for specific policies in areas with high carbon emissions, such as construction, energy,

TABLE 2 Objectives of central policies and laws.

Legislator	Law and regulation	Date of promulgation	Objective
Ministry of Ecology and Environment	Carbon Neutralization Implementation Guide for Large-scale Activities (Trial)	29 May 2019	To standardize the implementation of carbon neutrality for large-scale activities
Ministry of Education	Carbon Neutral Science and Technology Innovation Action Plan for colleges and universities	12 July 2021	To provide scientific and technological support and personnel guarantee for achieving carbon peak and carbon neutrality
Ministry of Ecology and Environment	Notice of the office of the National eco-industry Demonstration Zone Coordination Leading Group on promoting carbon peak and carbon neutrality of the national eco-industry demonstration zone	27 August 2021	Fully reflect the leading role of the national eco-industrial demonstration park in promoting the reduction of pollution and carbon synergy, promoting a regional green development model
The CPC Central Committee and the State Council	The CPC Central Committee and the State Council on the complete, accurate and comprehensive implementation of the new development concept to achieve peak carbon neutrality	22 September 2021	Bring carbon peak and carbon neutrality into the overall context of economic and social development, and ensure that carbon peak and carbon neutrality are achieved on schedule
The State Council	Carbon Peak Action Plan by 2030	22 September 2021	Bring carbon peak and carbon neutrality into the overall economic and social development, and ensure that these goals are achieved on schedule
State-owned Assets Supervision and Administration Commission	Guidelines on promoting high-quality development of central enterprises and achieving carbon peak and carbon neutrality	27 November 2021	Optimize the industrial structure and energy structure of central enterprises, and improve the energy utilization efficiency of key industries
National Development and Reform Commission, Cyberspace Administration of China, Ministry of Industry and Information Technology of China, National Energy Administration	Implement carbon peak and carbon neutrality targets, and promote green and high-quality development of new infrastructures such as data centers and 5G	30 November 2021	Promote the green and high-quality development of new infrastructure, represented by data centers and 5G
All-China Federation of Industry and commerce	Guidelines by the China Federation of Industry and Commerce on guiding private enterprises to achieve carbon peak and carbon neutrality	27 January 2022	Guide and serve private enterprises to achieve carbon peak and carbon neutrality
Ministry of Transport of China, National Railway Administration, Civil Aviation Administration of China, State Post Bureau	Guidelines by the Ministry of Transport, National Railway Administration, Civil Aviation Administration of China, and State Post Bureau on implementing the guidelines of the Central Committee of the Communist Party and State Council on implementing the new development concept in a complete, accurate and comprehensive manner to achieve peak carbon and carbon neutrality	18 April 2022	Achieve carbon peak in the transportation sector
Ministry of Education	work program to strengthen the carbon peak and carbon neutrality and personnel training system construction of higher education	19 April 2022	Improve the training quality of carbon peak and carbon neutral professionals
Treasury Department	Guidelines on Financial support for carbon peak and carbon neutrality	25 May 2022	Establish and develop a fiscal and tax policy framework conducive to green and low-carbon development
Standardization Administration of China	Circular on Standard and the plan for the National Carbon Peak and Carbon Neutrality and for the foreign language version of the relevant standards by Standardization Administration of China in 2022	21 July 2022	improve the standard system for carbon peak and carbon neutrality
National Energy Administration	Notice by the National Energy Administration of Issuing the Action Plan to Standardize Carbon Peaking and Carbon Neutrality in Energy	20 September 2022	Implement carbon peaking in the energy sector
The State Administration of Market Supervision, the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Natural Resources, the Ministry of Ecological	Establish and improve the implementation plan of carbon peak carbon neutralization standard measurement system	18 October 2022	Promote the construction of a carbon peak and carbon neutralization standard measurement system

(Continued on following page)

TABLE 2 (*Continued*) Objectives of central policies and laws.

Legislator	Law and regulation	Date of promulgation	Objective
Environment, the Ministry of Housing and Urban Rural Development, the Ministry of Transport, the China Meteorological Administration, and the State Forestry and Grassland Administration			

TABLE 3 Topic, quantity, and percentage share of local legislation and policies.

Topic	Quantity	Share (%)
Development of science and technology	28	35.44
Comprehensive	21	26.58
Finance	8	10.12
Fiscal	6	7.59
Education, training	5	6.33
Post and telecommunications	3	3.80
Construction	2	2.53
Energy	2	2.53
Agriculture	2	2.53
State-owned enterprises	1	1.27
Transportation	1	1.27
Total	79	100.00

transportation, and agriculture. This may be because local governments are concerned that policies to reduce emissions will hamper the region's economic development. However, the promotion of carbon neutrality in a region by encouraging technological innovation and earmarking, also in the local interest, can enhance the competitiveness of local enterprises at the national level. Therefore, in addition to promoting the development of science and technology, there are few policies and laws in the fields of finance, education, training, post, and telecommunications that have a less beneficial impact. In general, local initiatives to implement low-carbon development are not strong, and there are few policies and laws that impose rigid constraints, except through financial subsidies and incentives for specific research and development projects.

4.2 Characteristics and problems of China's carbon neutrality path

4.2.1 Characteristics of China's carbon neutrality path

China's carbon neutral policy and law are very comprehensive. Ideally, China's approach to carbon neutrality is based on the principles of national coordination, prioritizing of conservation, government-and market-driven coordination, coordination of domestic and international energy resources, and risk prevention. It is worth noting that, compared to other countries, China's carbon reduction efforts put more emphasis on strengthening the top-level design, giving full play to institutional advantages, and assigning equal responsibilities between the Communist Party and the government, encouraging some key areas, key industries, and places to take the lead in reaching the peak. From an economic standpoint, it is quite certain that what is right at the micro level is not always right at the macro level; on the contrary, what is right at the macro level may be very wrong at the micro level (Samuelson and Nordhaus, 2009). This fallacy of composition is, therefore, likely to trigger a crisis at the micro-governance level under more rigid emission reduction targets. China's emissions reduction policy clearly states that the relationship between pollution and carbon emission reduction, on the one side, and energy security, supply chain security of the industrial chain, food security, and people's normal lives, on the other side, should be well handled, effectively dealing with the possible economic, financial, and social risks associated with the green low-carbon transition, preventing overreaction and ensuring safe carbon emission reduction. China has integrated carbon peak into all aspects of its economic and social development. The "Carbon Peak Action Plan for 2030" sets out 10 key actions to be implemented, related to energy, industry, urban and rural construction, transportation, circular economy, scientific and technological innovation, carbon sequestration, and education for all. It can be seen that China's emission reduction framework not only is comprehensive, but also sets clear priorities to tackle key issues.

China's carbon neutrality is more emphasized on the rational use of administrative means. The implementation of China's carbon neutrality goal emphasizes both the government's and the market's efforts to build a new nationwide system. As a result, in addition to industrial policy and market instruments, China has adopted a more diversified approach to achieving carbon neutrality, reconciling its long-term, medium-term, and short-term goals. The executive branch approach has the following characteristics. First, it emphasizes the positive role of technological research and development and higher education. For example, the major initiatives set out in the Carbon Neutral

Science and Technology Innovation Action Plan of Colleges and Universities include training carbon-neutral talents, breakthroughs in basic research, tackling key technologies, enhancing innovation capacity, and promoting not only the transformation of scientific and technological achievements, but also international cooperation and exchange. Second, it establishes a variety of administrative guidance means. For example, the carbon neutrality implementation guidelines for large-scale events (pilot) encourage large-scale event organizers to develop a carbon neutrality implementation plan in the preparation phase of a large-scale event, to undertake mitigation actions in the implementation phase, and to account for greenhouse gas emissions and take offsetting measures to achieve carbon neutrality at the final stage. Third, it focuses on achieving carbon neutrality in development and on creating carbon reduction models. For example, the implementation of major regional strategies, such as the coordinated development of the Beijing-Tianjin-Hebei region, the development of the Yangtze River Economic Belt, the construction of the Guangdong-Hong Kong-Macao Bay Area, the integration of the Yangtze River Delta, and the ecological protection and high-quality development of the Yellow River Basin, focuses on strengthening the orientation and task requirements of green and low-carbon development. Fourth, it encourages key areas, key industries, and places with appropriate conditions to take the lead in reaching the carbon peak.

Local governments pay more attention to the effectiveness of discipline and technology iteration. Twenty-three of the local regulations and policies analyzed revolve around the promotion of science and technology. This shows the importance that local governments attach to facilitating the resolution of major technological bottlenecks and key scientific issues through policies, by combining the active layout of government departments with the demand-driven approach of market entities, to break through the neck of key core technology, improve the actual fulfilment of major scientific and technological achievements, and promote the upgrading of the industrial base and the modernization of the industrial chain.

4.2.2 The problems of China's carbon neutrality path

China's carbon emission reduction tools do not emphasize the application of financial instruments. China is following an ambiguous and complicated route in relation to the financial market rules and specialized regime of the carbon market. There are still no clear financial market laws and rules for carbon emission allowances (Chen and Wu, Forthcoming 2022). The development of the carbon market is a long-term process; hence, the role of government regulation has been highlighted under the rigid emission reduction constraints. At the same time, government regulation also faces the following problems.

The first problem is a lack of clarity. The realization of the vision on carbon peak and carbon neutrality will touch on the interests of multi-sector actors; therefore, the conflict and coordination of their interests need the strong intervention of the rule of law. However, to date, most of the laws and policies specifically focusing on emission reduction are advocacy-based, and the lack of clarity means that executive branches have room to abuse their power. These laws and policies do not include requirements on the production and management of enterprises as strict as those in the traditional environmental legislation. This creates some buffer space for enterprises to undertake emission reduction obligations; however, if the administrative power is abused, it will also cause the opposite effect. In China, the cost of breaking the law remains high due to the government's control of environmental pollution and related enterprises. Although some researchers believe that strict low-carbon enterprise responsibility is conducive to their green innovation, the opportunity cost of illegal investment in the process of green innovation is a more rational choice (Wang et al., 2022). However, in addition to the traditional environmental responsibility, in the short term, the imposition of excessive emission reduction costs will hinder the normal development of enterprises (Zhao et al., 2017). Clearer legislation would also impose more rigid constraints on local governments, and avoid the implementation difficulties that localism would create.

Second, the degree of public participation is low. A review of central and local regulations and policies revealed that, although the public is mentioned several times in various documents, it is only the target of knowledge and policy dissemination. Plenty of research showed that public participation can play an active role in addressing climate change, forming public opinion. In response to public demands, decision-makers will establish practical carbon allocation policies, which are based on the status quo of different subjects in social production and life. Thus, the realization of equity and efficiency values in the operation of the carbon market will be promoted (Peeters and Deketelaere, 2006). The EU's 2020 proposal for a European climate law, as well as the numerous revisions to the Carbon Market Directive, include public participation in addressing climate change and the carbon market and reinforce it as an important procedural rule. If China is to achieve higher emission reduction targets, it must increase public participation in emissions reduction to make legislation and policies more rational.

Third, existing policies and laws have a low rank. China has issued a comprehensive emission standard for air pollutants, specifying the emission limits for 33 types of air pollutants and various requirements for implementation. The standards set by regulation also provide a basis for the government or the environmental authorities to punish enterprises or individuals emitting air pollutants that exceed the standards or emitting unauthorized air pollutants. However, although local governments tend to compete in the setting of ambitious goals for pollution emission reduction, in practice there is no corresponding accountability system (Yang et al., 2020). The public or enterprises cannot sue carbon-emitting enterprises just as they sue pollution-discharging enterprises. If too many legislative matters are handed over to local governments, it will be difficult to implement them due to the lack of legal cooperation. Even though there are no technical barriers to monitoring greenhouse gases, it is difficult to sue the energy sector for excessive emissions, or the governments for failing to fulfil their duty (He, 2021). In China, decentralized and fragmented laws and regulations make it difficult for various systems to create systematic synergies for climate change mitigation, thereby reducing the benefits of law enforcement and increasing the cost of social governance. In 1998, Japan formulated the policy-oriented "Global Warming Countermeasures and Promotion Law", which was the prelude of national legislation on climate change. At the end of 2009, around the Copenhagen Climate Conference, the international community saw a peak in climate legislation. In 2008, the United Kingdom passed the "Climate Change Act", which was a pioneering step in including greenhouse gas emission reduction targets into law, setting for the first time a carbon budget system and a special authority. In 2009, the Philippines introduced a policy-based "Climate Change Act". In 2010, the Republic of Korea issued the "Basic Law on Low-Carbon Green Growth", a policy-oriented and framework legislation, while in 2012 Mexico adopted the "Basic Law on Climate Change", which specified emission reduction targets and set up a management body. In the following years, France, Germany, Denmark, Norway, and Finland also introduced specific legislation aimed at reducing carbon emissions. Given the current legislative situation of China, with a decentralization that is not exerting the resultant force, the backward policy implementation, and the local legislation lacking the upper-level law to rely on, it is more suitable to make a special law to solve these problems.

5 Conclusion and policy recommendations

Carbon neutrality does not entail a simple emission reduction goal, but rather broad and profound economic and social systemic changes. China has developed a top-level guidance plan for carbon peak and carbon neutrality and needs to make appropriate use of a wide range of policy tools, including legal, economic, technological, market, and financial instruments. Strengthening the design of synergies among different policy objectives and instruments, and gradually establishing a complete and effective policy and legal system, will help promote the transformation and reshaping of the energy system and achieve an effective low-carbon transition. As the world's factory and late developing country, China has undertaken important emission reduction tasks. To achieve the goal of carbon neutrality while maintaining economic growth requires an effective cooperation between the central government and local governments. A clearer, higher-level, and enforceable legal system needs also to be established. If China can achieve the emission reduction targets as scheduled, its legislative model can also be a feasible example for other developing countries. Based on this analysis, the following suggestions are advanced:

1) Improve carbon finance rules. China has already created a specialized regime for the spot carbon market. To reduce the pressure of government regulation, carbon finance laws should be improved. Effective financial market rules can help build carbon neutral infrastructure. Therefore, a new approach to connect the carbon market rules and financial market rules should be developed.
2) Timely promulgation of the climate change law. Climate change is a complex global problem. The enactment of this law will support the development of low-carbon related fields such as ecological protection, energy sustainability, and circular economy. The regulation of low-carbon development in various fields in the form of legal principles could solve the problem of fragmentation of legislation. After clarifying the legal objectives, basic principles, management bodies, mitigation and adaptation system measures, and accountability mechanisms, other laws and regulations should also be amended to incorporate the concept of low-carbon development, including the "Electricity Law", the "Air Pollution Prevention Law", the "Circular Economy Promotion Law", the "Forest Law", and the "Grassland Law".
3) Increase citizen participation in policy-making and implementation. It is necessary and feasible to integrate public participation mechanisms into the legislative processes of China's carbon emissions trading legislation, especially the quota allocation. In the legislative path, we can choose the specific way to legalize the mechanism of public participation, and design a specific system aiming at the main content, scope, and mode of participation, so as to improve the rationality of policy-making.

4) Establish a public interest litigation system on climate change to restrain the executive power. As a branch of environmental public interest litigation, climate change public interest litigation has already been practiced across the world (Gerrard, 2007). In China, central and local policies have led to high coal prices, power cuts, and coal shortages in some places, highlighting the potential for abuse. Although the central government has made it clear that it wants to avoid the social risks associated with reducing emissions, the COVID-19 pandemic has pushed

local governments to make irrational decisions because of a fallacy of composition, which has a major impact on citizens' lives. The existence of a public interest litigation system on climate change can not only restrain the government from actively performing its duties to promote emission reduction, but also limit the government's abuse of power and excessive emission reduction.

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

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1043404/full#supplementary-material

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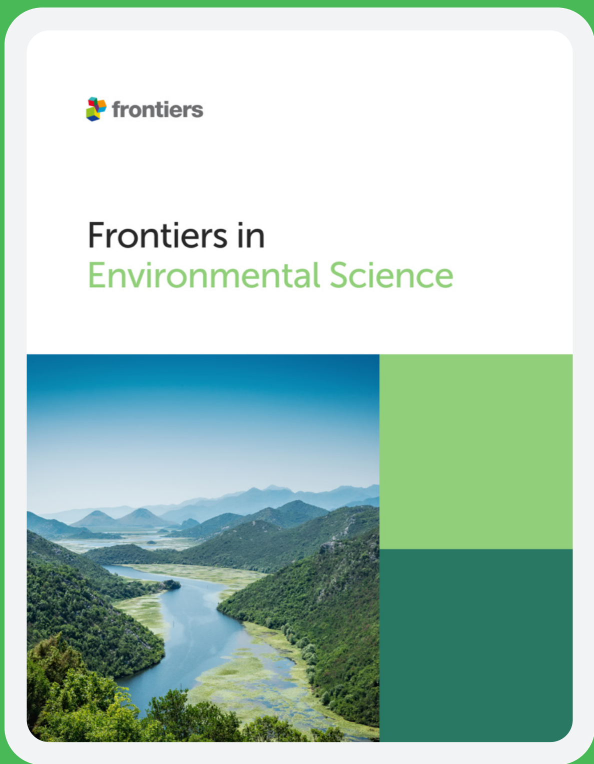

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