frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 16 January 2026
DOI 10.3389/fsufs.2025.1727846

OPEN ACCESS

EDITED BY
Safdar Hussain,
Pir Mehr Ali Shah Arid Agriculture University, Pakistan

REVIEWED BY
Shahid Mahmood,
University of Sargodha, Pakistan
Rana Muhammad Sohail Jafar,
Al Yamamah University, Saudi Arabia

*CORRESPONDENCE
Xutian Qin
✉ 617403290@qq.com

RECEIVED 18 October 2025
REVISED 08 December 2025
ACCEPTED 18 December 2025
PUBLISHED 16 January 2026

CITATION
Xu X, Wang L and Qin X (2026) Mechanisms influencing green technology innovation efficiency in China's food industry: a TOE-framework perspective guided by food safety assurance.
Front. Sustain. Food Syst. 9:1727846.
doi: 10.3389/fsufs.2025.1727846

Mechanisms influencing green technology innovation efficiency in China's food industry: a TOE-framework perspective guided by food safety assurance

Xiaodong Xu[1], Likun Wang[1] and Xutian Qin[2]*

[1]School of Management, Dalian Polytechnic University, Dalian, Liaoning, China, [2]School of Business Administration, Zhongnan University of Economics and Law, Wuhan, Hubei, China

Introduction: Against the dual backdrop of global low-carbon transition and food safety upgrading, Green Technology Innovation (GTI) has become pivotal for the transformation of China's food industry. However, existing research largely relies on linear or single-factor analytical frameworks, overlooking the synergistic and configurational effects among multi-dimensional factors. As a result, the internal mechanisms driving GTI efficiency remain insufficiently explored.
Methods: This study is grounded in a food-safety-oriented Technology-Organization-Environment (TOE) framework, this study adopts a configurational, by applying Necessity Condition Analysis (NCA) and fuzzy-set Qualitative Comparative Analysis (fsQCA) to cross-sectional data from 30 Chinese provinces.
Results: (1) Achieving high GTI efficiency requires multi-factor synergy, and no single condition is sufficient independently. (2) Food safety testing investment, green production momentum, and R&D innovation capacity are identified as critical necessary factors for high GTI. (3) The analysis reveals three types of high-efficiency pathways, namely by Innovation-Safety-Led, Market-Environment-Driven, and Policy-Resource-Coordinated models, demonstrating mechanism equifinality.
Discussion: This study innovatively integrates the food safety perspective, enriches the configurational theory of GTI, and offers practical insights for formulating differentiated and synergistic green development policies.

KEYWORDS
food industry, food safety, fsQCA, green tech innovation, NCA, TOE framework

1 Introduction

Global climate change is accelerating at an unprecedented pace, as confirmed by the World Meteorological Organization (WMO) 2023 report, which underscores the urgent need for a green transition within the resource-intensive food industry. As the world's largest food producer, China's food sector has prioritized green technological innovation (GTI) to achieve carbon peak and carbon neutrality goals while ensuring food security. Specifically, GTI connects the two goals: Precision agriculture reduces emissions while boosting yield; energy-efficient processing and eco-friendly packaging lower carbon footprints and ensure quality; circular technologies convert waste into usable resources.

Against this backdrop, this study addresses two core research questions: (1), which technologies, organizational structures, and environmental conditions can support high GTI efficiency in the food industry? (2), how do food safety-related factors interact to influence GTI performance under different combinations of these conditions? However, existing research predominantly relies on single theoretical frameworks. The Resource-Based View (RBV) emphasizes internal resources but tends to overlooks external constraints, while Strategic Management Theory (STM) emphasizes strategic orientation but insufficiently considers the interaction between technological investment and organizational management. Methodologically, most existing research primarily relies on quantitative regression analysis to examine unidirectional causal relationships between green technology innovation performance and individual (such as funding or policy), failing to dissect the interactive mechanisms and dynamic evolutionary processes among multiple factors—this constitutes a critical research gap.

To address the aforementioned issues and fill research gaps, this study innovatively adopts the Technology-Organization-Environment (TOE) framework. This framework integrates internal corporate capabilities, external constraints, and core technological elements, effectively circumventing the limitations of single-theory frameworks. The contribution of TOE application is reflected across three dimensions: theoretical, operational, and empirical. Theoretically, food safety elements are embedded within the TOE framework to broaden its applicability. Operationally, the framework integrates fuzzy-set Qualitative Comparative Analysis (fsQCA) and Necessary Condition Analysis (NCA), to convert the three dimensions into measurable variables. At the empirical level, the period from 2013 to 2022 is divided into two stages to enable dynamic comparative analysis.

Using 30 Chinese provinces as research samples, this study founds that high GTI performance in the food industry depends on the integrated interaction of three-dimensional factors: technology, organization, and environment. Food safety elements further enhance green technology innovation through pathways such as building market trust and standardizing innovation processes. The research conclusions provide a reference basis for local governments to formulate targeted policies.

2 Literature review and theoretical foundations

2.1 Literature review

2.1.1 Technical antecedents

Technological factors serve as the core driver for enhancing the efficiency of green technological innovation in the food industry, primarily reflected in three dimensions: digital technology application, safety technology R&D, and technological infrastructure development. Green technological innovation in the food industry encompasses diverse forms such as pollutant detection in aquaculture and fisheries, as well as clean-production practices. Safety-technology R&D not only reduces food safety risks by enhancing detection accuracy but also enhances resource-utilization efficiency, providing concrete pathways to drive innovation efficiency at the technical level (Lin et al., 2023).

The increasing integration of digital technologies injects new momentum into enhancing the efficiency of green technological innovation. The development of the digital economy can strengthen food safety oversight and promote industrial green transformation through technological innovation, thereby boosting the efficiency of green technological innovation. This effect exhibits significant heterogeneity due to regional development disparities (Fei et al., 2025). Digital technologies such as block chain effectively address food traceability challenges by establishing secure and reliable data systems, becoming a core pillar of modern food safety. Nonetheless, insufficient digital R&D may hinder the effectiveness of commercializing outcomes, and the higher the level of digital economic development, enhance the practical effectiveness of technology implementation (He and Yu, 2025). As an newly emerging digital technology, the metaverse also provides additional pathways for green technological innovation. Research integrating the TOE framework with the Resource-Based View reveals that the metaverse can reduce physical resource consumption through virtual collaboration. AI-driven predictive analytics and related technologies can promote metaverse adoption, while informed decision-making serving as critical determinant influencing adoption. These insights offer meaningful implications for the food industry in improving innovation efficiency through deeper digital technology integration (Jabeen et al., 2025).

From the perspectives of industrial integration and consumer demand, digital industrial clusters can improve green economic efficiency in the food industry through the mediating role of technological innovation (Xin, 2025). Meanwhile, the metaverse can enhance consumer engagement and immersion by creating interactive experience environments. These consumer-oriented digital technology applications can in turn drive food enterprises to optimize their technological innovation directions and increase the effectiveness of innovation conversion (Jafar et al., 2025).

Additional cross-industry research from cross-industry research further validates the core role of green technological innovation in driving corporate green performance. Using Pakistan's textile industry as an example, Mahmood et al. (2025) demonstrated that green technological innovation, alongside eco-design and environmental behavior, exerts a positive effect on the success of green new product development. This relationship is partially mediated by green process innovation (and is not suppressed by green product innovation) and moderated by green corporate image. Their findings deepen the empirical understanding of how technical factors translate into tangible green innovation outcomes, highlighting that technological antecedents not only must interact with organizational practices and corporate image with organizational behaviors and image building to maximize performance impact—insights that are likewise relevant to the food industry's green technology transformation (Mahmood et al., 2025).

2.1.2 Organizational antecedents

Organizational-level coordination mechanisms, governance structures, and resource integration capabilities play a decisive role in diving or constraining the efficiency of green technological innovation within the food industry. Food enterprises frequently encounter challenges during the implementation of green technological innovation, including high compliance costs associated with food safety standards, shortages of specialized resources, and weak internal coordination. Among these, poor organizational coordination has identified as a key obstacle requiring prioritized improvement (Madilo et al., 2024).

Evidence from TOE-based analyses and co-governance cases indicates that multi-stakeholder participation and institutional integrity are core conditions for improving technology transfer efficiency, while the absence of integration mechanisms significantly reduces the impact of technological empowerment (Hu and Wu, 2025). From a supply-chain perspective, corporate quality investment costs and organizational coordination mechanisms are key determinants of technology application efficiency. The "gatekeeper mechanism" between platforms and live streamers functions as a critical organizational safeguard, promoting the effective implementation of technical standards (Wu and Chen, 2024; Ma et al., 2025). In agricultural enterprise practice, institutional embeddedness and social-trust relationship strengthen organizational synergy effects. These mechanisms complement industry-academia-research collaboration, effectively enhancing the linkage between R&D and technology transfer stages (Dong and Qi, 2025).

2.1.3 Environmental antecedents

External environmental factors such as policy instruments, market mechanisms, and standards systems exert systemic influences on the efficiency of green technological innovation within the food industry by establishing incentives or constraints mechanisms for innovation. Regarding policy instruments, environmental taxes can stimulate increased R&D investment among agro-forestry and food processing enterprises, alleviating financial barriers and promoting green technological innovation practices. This offers empirical support for the effectiveness of such policy instruments (Hu et al., 2025). This approach to policy intervention is likewise applicable in the international agricultural and food sector. For instance, studies on Pakistan's rice industry indicate that environmental factors such as insufficient agricultural R&D investment and inefficient trade policies restrict industrial development. Regulatory interventions, including trade policies optimization and increased R&D subsidies, can effectively enhance industrial competitiveness, offering valuable international reference for the food industry to enhancing the food industry's innovation environment through policy instruments (Jafar et al., 2015). The efficacy of different policy instruments varies, with mandatory tools demonstrating the most significant impact on green technological innovation efficiency. Guiding and voluntary instruments have yet to realize their full potential, and regional institutional environments exert a moderating effect on policy tool outcomes (Dzwolak and Anim, 2025).

Market mechanisms and standards systems, as vital environmental factors, also serve as critical environmental factors. Commercial credit financing can offers indirect resources support for corporate green technological innovation through pathways such as promoting product innovation and strengthening supplier supervision, thereby supplementing the environmental dimension of market mechanisms (Zhang et al., 2025). From the perspective of consumer market influence, digital communication channels such as social media and green blogs can significantly shape consumers' green purchasing intentions, with social media trust acting as a moderating factor. This demand-side green preference can in turn incentivise enterprises to increase investment in green technological innovation, forming a key pathway for market environment-driven innovation (Ahmad et al., 2023). Food-safety standard systems can enhance innovation efficiency by directing technological R&D and promoting quality upgrades, with this catalytic effect being particularly evident during technology transfer in primary agricultural products (Gao, 2025). Moreover, efficient government regulatory services and robust market oversight mechanisms provide stable resource support for innovation, whereas institutional deficiencies can hinder the positive outcomes of technological innovation (Li and Fu, 2023; Zhu et al., 2025).

2.1.4 Food safety as a regulatory element

Food safety, as the core value orientation of the food industry, exerts a significant regulatory influence throughout the formation process of green technological innovation efficiency. This regulatory effect permeates the entire trajectory of technological research and development, organizational coordination, and environmental responsiveness. As a foundational industry for public welfare, the food sector faces dual pressures: ensuring food safety and the imperativing resource-utilization efficiency. These challenges collectively constitute the underlying driving force for green technological innovation, positioning food safety objectives as the central anchor point for green technology research and development (Liu and Zhang, 2025).

From a technological application perspective, the efficiency gains from green technological innovation are strongly and positively associated with food safety assurance. The R&D and development of green technologies, such as pollutant detection and traceability tracking have simultaneously enhanced innovation efficiency and strengthened food safety governance capabilities, thereby establishing a virtuous cycle of 'technological innovation–safety assurance–efficiency enhancement' (Zhang et al., 2024). At the regional level, the shows a 'high regulation-high efficiency' clustering pattern with green technological innovation efficiency. This indicates that stringent food safety oversight can enhance green technological innovation efficiency by strengthening innovation incentives (Yao and Pan, 2025).

Within the interaction between organizations and their environment, food safety also plays a regulatory role in problems such as weak organizational coordination and insufficient multi-stakeholder participation. Issues such as inadequate organizational coordination and the absence of multi-stakeholder participation simultaneously impact both the effectiveness of food safety governance and the efficiency of green technology transformation. Conversely, a well-developed organization coordination mechanism can achieve synergistic enhancement of both (Hong et al., 2025). When policy instruments and standards systems are designed with food safety as the core orientation, their driving effect on the efficiency of green technology innovation becomes more pronounced. For instance, the promotional role of food safety standards in technology transformation is achieved precisely by converting safety objectives into innovation concrete and incentives (Jiang et al., 2025).

2.2 The TOE framework theory

The TOE framework is a classical analytical model for examining how technological, organizational and environmental factors jointly influence green technological innovation processes within China's food industry. When integrated with a food-safety assurance orientation, it can more accurately capture the sector's distinctive mechanism of influence. At the technological level, this encompasses green food processing R&D capabilities, breakthroughs in food safety detection technologies, and practitioner expertise which together from the bedrock and driving force of innovation. These three elements constitute a progressive support system: specialized food education provides talent and knowledge resources for research and employment in R&D and safety detection, while breakthroughs in scientific practice accelerate the conversion of educational resources into 'green + safety' technological achievements. The organizational dimension encompasses food enterprises' green production momentum, government-specific green fiscal support for the food sector, and collaborative food safety regulatory mechanisms. This constitutes the internal support system for innovation, forming a bidirectionally empowering synergistic mechanism: corporate demand for green production transformation guides the implementation of green fiscal policies; targeted fiscal support activates innovation momentum; regulatory mechanisms compel enterprises to align innovation with safety control objectives. The environmental dimension encompasses clean energy supply guarantees for food supply chains, resource recovery systems for food processing waste, consumer preferences for green and safe food, and the industry's dual environmental and safety standards. This constitutes a vital external driving field, forming a multidimensional system in which clean energy guides the direction of processing technology, waste treatment technologies ensure supply chain sustainability, and consumer preferences and industry standards transform external demands into endogenous momentum.

Analysis of these three dimensions clarifies their respective weightings and transmission pathways that influence GTI efficiency. Crucially, it uncovers the complex, cross-linked relationships between these factors, providing scientific grounds for enterprises to align their 'green + safety' R&D directions and for governments to optimize supportive and regulatory policies. This enhances innovation success rates and the conversion of benefits, bolsters the industry's core competitiveness in the era of green economy and safe consumption, and propels the sector towards a sustainable paradigm characterized by 'safety and controllability, low-carbon and high efficiency'.

Drawing upon the research approach of Wang et al. (2023). This paper employs the TOE theoretical framework to analyze the efficiency of green technological innovation within the food industry. By deconstructing the core factors and their interrelationships across three dimensions—Technology (T-FOOD), Organization (O-FOOD), and Environment (E-FOOD)—it clarifies the weighting and transmission pathways of each factor's influence on the industry's efficiency in green technological innovation. This approach uncovers the complex, cross-linked interactions between factors, providing a scientific basis for enterprises to align their 'green + safety' R&D directions and for governments to optimize supportive and regulatory policies.

2.2.1 T-FOOD

The technological dimension serves as the bedrock and driving force behind green technological innovation in the food industry. Its core encompasses two pivotal dimensions: specialized food education and technological research and development, as well as food safety testing technologies. These form an organically integrated system characterized by tiered support and dynamic interconnection. Within this framework, the educational component of specialized food education and technological R&D provides the core talent pool and knowledge reserves for both R&D practice and safety testing domains, directly determining practitioners' professional competence levels. Conversely, practical breakthroughs in technological R&D and food safety testing technologies drive deeper alignment between educational content and industrial demands, accelerating the closed-loop conversion of 'knowledge–technology–outcomes.' Specifically, targeted enhancement of the academic component in food science education and technological R&D strengthens the talent base for research practice and safety testing. Conversely, upgrades in R&D capabilities and innovations in testing technologies continuously inject cutting-edge industrial demands into the educational system. This ensures sustained technological innovation vitality, fostering a virtuous cycle where 'education and R&D synergistically empower testing, while testing in turn enriches education.'

2.2.2 O-FOOD

At the organizational level, the internal support system for green technological innovation in the food industry comprises two key elements: corporate green production momentum for and dedicated government green fiscal support. These form a bidirectional, mutually empowering collaborative mechanism. Food enterprises' demand for green production transformation provides a clear direction for the precise implementation of government green fiscal policies, preventing policy disconnect from market needs. Meanwhile, dedicated government green fiscal support offers financial safeguards for corporate innovation, effectively activating the endogenous momentum for green technological R&D within enterprises. Enterprises deeply integrate green technological innovation with safety management objectives, relying on both their own transformative drive and on government policy guidance and financial support. This 'enterprise demand-policy support' interaction model enhances the resource allocation efficiency of innovation momentum and strengthens the supporting role at the organizational level.

2.2.3 E-FOOD

The environmental dimension is a crucial external driver for green technological innovation in the food industry, encompassing two core elements: energy consumption and waste management. These form a mutually reinforcing external driving system. The green transition in the food industry's energy consumption directly guides the direction of processing technology innovation, driving carbon emission reductions in production processes. Meanwhile, the refinement of food processing waste management systems safeguards supply chain sustainability, providing practical scenarios for green technological innovation. These two elements form complementary synergies from the perspectives of resource utilization and circular development, optimizing foundational production conditions while clarifying innovation pathways. Together, they foster a favorable external environment for green technological innovation within the food sector.

Technology (T), Organization (O) and Environment (E) interact organically to enhance green technological innovation efficacy within the food industry collectively. Within T, two elements complement each other: food education and R&D supply specialized personnel for safety testing, while breakthroughs in testing feed back into optimizing educational content. At the organizational (O) level, a synergistic

10.3389/fsufs.2025.1727846

empowerment loop forms, where enterprises' demand for green production guides government implementation of targeted fiscal support, thereby effectively activating corporate R&D momentum. Within Environment (E), energy consumption transformation and waste management similarly reinforce one another: green energy guides technological innovation, while waste treatment systems provide practical innovation scenarios. At the cross-system level, O's fiscal support drives R&D and testing technology upgrades in T, At the same time, E's resource circulation demands propel technological iteration in T. Conversely, T's innovations both assist enterprises in achieving green development goals (O) and meet E's low-carbon development requirements. This cross-linkage optimizes innovation resource allocation, enabling precise alignment with market and policy demands while clarifying R&D pathways. This collectively enhances the efficacy of innovation and propels industrial sustainability. The resulting research model (as illustrated in Figure 1) clearly visualizes the interactive relationships among these elements and their combined impact on innovation efficiency.

3 Research design

3.1 Research methods

This paper employs a combined approach of Necessity Condition Analysis (NCA) and fuzzy set Qualitative Comparative Analysis (fsQCA) for the following reasons. Firstly, integrating these two methodologies requires a robust theoretical framework that aligns with the study's causal logic. Building on the TOE theoretical framework, this study categorizes factors influencing the efficiency of green technological innovation in the food industry into three dimensions: technological, organizational, and environmental. Extensive academic research has elucidated the interactive relationships among antecedent variables and their associations with outcome variables within this framework (Wang et al., 2023), providing a robust theoretical foundation for the combined methodology. Concurrently, the core research questions center on 'how multiple factors synergistically drive high innovation efficiency' and 'whether necessary preconditions exist.' The core value of NCA lies in identifying necessary conditions through upper-bound regression analysis (CR) and upper-bound envelope analysis (CE) (Ragin, 2008). Whereas, fsQCA excels at analyzing the configurational effects of multiple antecedent conditions. Existing research confirms that QCA results often constitute a subset of NCA findings. Their combined application forms a logical closed-loop approach—'first testing necessity, then analyzing sufficiency'—ideally suited to the causal structure requirements of this study. Secondly, regarding sample size and condition number compatibility, existing research indicates that fsQCA is suitable for small to medium-sized samples of 10–50 cases, with an ideal condition range of 4–7 (Teng, 2023). NCA, however, shares highly compatible sample-size requirements with QCA, enabling robust analysis without requiring large samples. This

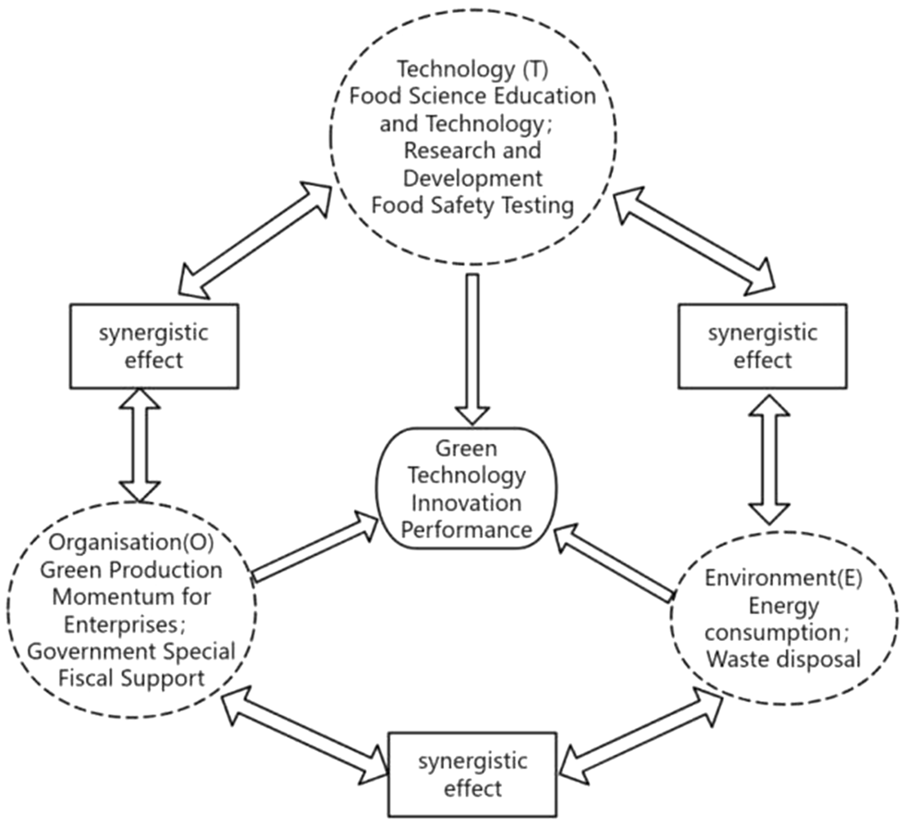

FIGURE 1
TOE research model for green technological innovation performance.

study selected 30 Chinese provinces as research samples, meeting the small-sample requirement of classical QCA analysis. Six antecedent conditions were established: food-specialized education and technological R&D, food safety inspection, corporate green production momentum, government specialized fiscal support, energy consumption, and waste treatment.

This configuration falls precisely within the suitability ranges of both methods, effectively avoiding result biases caused by insufficient sample size or excessive conditions settings. Thirdly, regarding methodological adaptability, the combined use of NCA and fsQCA offers distinct advantages over traditional approaches such as DEA (focused on input–output efficiency measurement) and SEM (focused on linear path relationships). On one hand, NCA addresses the shortcomings of conventional methods that 'over emphasize impact while under emphasizing necessary logic,' clearly revealing essential bottleneck conditions across varying innovation levels. On the other hand, fsQCA not only handles categorical issues but also addresses fuzzy attribution problems involving degree variation (where case attribution scores range between 0 and 1). It can incorporate multiple combinations of antecedent conditions and analyze of dynamic evolutionary patterns. Both methods support cross-period comparative analysis, enabling the capture of configuration differences and regional transformation patterns across the 2013–2017 and 2018–2022 periods. A capability beyond the scope of DEA and SEM.

3.2 Sample selection and data collection

To ensure the comprehensive sample availability and the sustainability of subsequent research, this study selected 30 provinces and municipalities in China as the case sample, with the research period set from 2013 to 2022. Data from this 2013–2022 captures changes before and after the introduction of the"dual carbon"goals while effectively ensuring the timeliness of the research questions. Furthermore, the sample size of 30 provinces meets the small-sample requirements of classical QCA analysis. In summary, selecting data from 30 Chinese provinces spanning 2013–2022 meets research needs. Data sources include the National Bureau of Statistics of China, the China Statistical Yearbook, and provincial statistical yearbooks.

3.3 Variable measurement and calibration

Table 1 presents the measurement and weighting of variables related to the efficiency of green technological innovation in the food industry.

The outcome variables selected to measure this efficiency comprise the Food Industry Green Finance Development Index (a composite indicator gauging the sector's green finance development level, calculated form officially published index values) and green patent authorizations (the number of industry-related green technology patents granted, calculated from actual statistical counts).

Among the independent variables, the technological dimension is evaluated through two dimensions: development capacity and comprehensive quality capability. Development capacity encompasses food industry education and training expenditure (measured using expenditure amounts in billions of yuan) and specialized personnel in green food technology (calculated based on personnel measured in ten thousand). Comprehensive quality capability includes the number of food industry R&D and safety testing units (calculated from actual unit counts) and the number of testing personnel (calculated based on 10,000).

The organizational dimension is analyzed across two dimensions: comprehensive economic development level and ecological environment construction. The extensive economic development level includes gross value added in the food industry and green investment (both calculated from actual expenditure figures in billion yuan). Ecological environment construction includes special environmental protection expenditure in the food industry (calculated from actual expenditure figures in billion yuan) and the green coverage rate in the built-up areas of concentrated food production zones (calculated as a percentage).

The environmental dimension is examined through energy security and environmental impact. Energy security encompasses electricity consumption for food industry production (in billion kilowatt-hours) and water consumption for production (in billion cubic meters). Environmental impact includes non-polluting treatment rate of food industry waste (calculated as a percentage) and treatment volume (calculated in tonnes).

All variable definitions align with their core measurement principles, with data sourced from the National Bureau of Statistics of China, the China Statistical Yearbook, and provincial statistical yearbooks.

3.3.1 Data calibration

Calibration is the critical step in converting case data into set membership scores. To achieve precise calibration of variables, the direct calibration method is selected. This method assigns set membership scores to given cases, enabling a more scientific and practical approach to avoiding subjective weighting and reducing human error. Referencing the research by Zhou et al. (2023), the three calibration points—complete membership, crossover point, and complete non-membership—for antecedent and outcome variables were set as the upper quartile (75%), median (50%), and lower quartile (25%), respectively. Table 2 presents the calibration data for each antecedent and outcome variable within Time Slot 1 and Time Slot 1.

4 Empirical analysis

4.1 Necessary condition analysis

Necessary Condition Analysis (NCA) employs two methods to obtain effect sizes: Upper Bound Regression Analysis (CR) and Upper Bound Envelope Analysis (CE). In this approach, the necessary condition must satisfy two criteria: the effect size must exceeds 0.1, and the Monte Carlo permutation test must yields a significant results ($p < 0.01$).

The results are shown in Table 3. For Time Slot 1, Food Safety Testing meets the necessary condition, with an effect size of 0.107 (exceeding 0.1) and a statistically significant p-value of 0.000 ($p < 0.01$). For Time Slot 2, all conditional variables have effect sizes less than 0.1, and thus no necessary conditions are identified in this period.

Table 4 presents the bottleneck-level analysis results based on the NCA methodology, focusing on the necessary condition identified in

TABLE 1 Measurement and weight of antecedent variables.

Level 1 variable	Level 1 indicators	binary variable	Secondary indicators	bibliography
Technical level	Capacity for development	Food science education and technology R&D	Food industry training and education funding (0.5)	Moran et al. (2024)
			Specialists in green food technology (10,000) (0.5)	Hu and Chen (2025)
	Comprehensive competency	Food safety testing	Number of the food industry R&D and safety inspection units (0.5)	Liu et al. (2024)
			Number of personnel in food industry R&D and safety inspection (10,000 persons) (0.5)	Liu et al. (2024)
Organizational level	Comprehensive level of economic development	Green production momentum for enterprises	Food industry gross value added (RMB billion) (0.5)	Zou et al. (2024)
			Green investment in the food industry (RMB billion) (0.5)	Sanguinet and García (2023)
	Ecological environment development	Government special fiscal support	Environmental protection expenditures in the food industry (RMB 100 million) (0.5)	Yuan et al. (2025)
			Green coverage rate (%) in built-up areas of food production clusters (0.5)	Zhu et al. (2023)
Environmental level	Energy security	Energy consumption	Electricity consumption for food industry production (100 million kilowatt-hours) (0.5)	Xiaozhi et al. (2023)
			Water consumption in food industry production (100 million cubic meters) (0.5)	Xiaozhi et al. (2023)
	Environmental impact	Waste disposal	Non-polluting treatment rate of food industry waste (%) (0.5)	Vialkova et al. (2024)
			Non-polluting treatment volume of food industry waste (tons) (0.5)	Vialkova et al. (2024)
Green technology innovation performance in the food industry		Financial support for the food industry	Green finance development index for the food industry (0.5)	Trusova et al. (2025)
		Innovation capability in the food industry	Number of green patent authorizations in the food industry (0.5)	Batool et al. (2025)

Time Slot 1 (Food Safety Testing) and on the context of a specific target—"achieving 90% green technological innovation efficiency." In NCA methodology, necessary conditions can be analyzed both "in kind" (whether a condition is generally required for the outcome) and "in degree" (the specific level of the necessary condition for a particular level of the outcome).

For the specific target of 90% green technological innovation efficiency, NCA identifies three conditional variables that require minimum thresholds to be met (even if some do not qualify as overall necessary conditions for green technological innovation performance across all outcome levels): specialized food education and technological R&D (0.8%), energy consumption (1.9%), and food safety testing (10.6%) (where "10.6/10.6" in the table indicates this threshold remained stable across both time periods). No bottleneck levels were identified for the remaining conditions.

It should be clarified that the minimum thresholds for Food Science Education and Technology R&D and Energy Consumption are specific to this high-efficiency target—they are necessary conditions for achieving this particular outcome level, rather than essential conditions for green technological innovation performance in general (which requires meeting the NCA criteria of effect size>0.1 and $p < 0.01$). In contrast, Food Safety Testing is both a general necessary condition (for Time Slot 1) and a specific threshold condition for the 90% efficiency target. The core implication of the 10.6% threshold for food safety testing is that if its level falls below this value, achieving 90% green technology innovation efficiency becomes

TABLE 2 Calibration anchor points of fuzzy sets in each period.

The twelve 2 h divisions of the day	Time Slot 1			TIME SLOT 2		
Assembly	Wholly subordinate	Intersection	Not affiliated in any way	Wholly subordinate	Intersection	Not affiliated in any way
Green technology innovation	0.070	0.0168	−0.012	0.288	0.174	0.126
Food science education and technology R&D	0.126	0.0789	0.051	0.151	0.109	0.064
Food safety testing	0.212	0.120	0.065	0.227	0.118	0.0618
Green production momentum for enterprises	0.331	0.251	0.208	0.318	0.237	0.180
Government special fiscal support	0.522	0.460	0.394	0.446	0.341	0.266
Energy consumption	0.343	0.243	0.145	0.362	0.217	0.131
Waste disposal	0.239	0.164	0.106	0.270	0.164	0.101

TABLE 3 Analysis results of the necessary conditions of NCA methods in different periods.

Conditions	Method	Time Slot 1			Time Slot 2		
		Accuracy	Effect size	*P*-value	Accuracy	Effect size	*P*-value
Food science education and technology R&D	CR	100%	0.012	0.000	100%	0.005	0.000
	CE	100%	0.012	0.000	100%	0.005	0.000
Food safety testing	CR	100%	0.107	0.000	100%	0.019	0.000
	CE	100%	0.107	0.000	100%	0.019	0.000
Green production momentum for enterprises	CR	100%	0.033	0.000	100%	0.002	0.000
	CE	100%	0.033	0.000	100%	0.002	0.000
Government special fiscal support	CR	100%	0.021	0.000	100%	0.000	1.000
	CE	100%	0.021	0.000	100%	0.000	1.000
Energy consumption	CR	100%	0.009	0.000	100%	0.003	0.000
	CE	100%	0.009	0.000	100%	0.003	0.000
Waste disposal	CR	100%	0.009	0.000	100%	0.010	0.000
	CE	100%	0.009	0.000	100%	0.010	0.000

untenable; reaching this threshold merely satisfies a "necessary condition," and the target can only be realized if the other two specific threshold conditions are simultaneously met.

Further conduct a necessary condition analysis using fsQCA, observing Table 5 with reference to the consistency threshold of 0.9.

Observing Table 5 reveals that the consistency coefficients for variables such as food science education, technological R&D, food safety testing, corporate green production momentum, and government-specific fiscal support all fall below 0.9. Due to differing approaches to determining necessary conditions, the NCA method identifies necessary conditions at different levels of outcome variables by shifting upper bounds or by rotation. In contrast, the QCA method primarily uses the diagonal of scatter plots as a reference line to identify necessary conditions for high outcome variables.

Consequently, QCA results are often a subset of NCA results. From the perspective of general necessary conditions (meeting NCA's effect size >0.1 and $p < 0.01$), only Food Safety Testing in Time Slot 1 qualifies as an essential condition for green technological innovation performance. No general necessary conditions are identified in Time Slot 2, and none of the conditional variables meet the QCA consistency threshold of 0.9 (Table 5), indicating no QCA-identified necessary conditions across all time periods. However, for the specific target of '90% green technological innovation efficiency', three conditional variables (Food Science Education and Technology R&D, Energy

TABLE 4 Analysis results of NCA bottleneck level (%) in each period.

Green technology innovation	Food science education and technology R&D	Food safety testing	Green production momentum for enterprises	Government special fiscal support	Energy consumption	Waste disposal
0	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
10	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
20	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
30	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
40	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
50	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
60	0.1/0.1	NN/NN	NN/NN	NN/NN	NN/NN	0.2/0.8
70	0.4/0.4	1.5/0.5	NN/NN	NN/NN	NN/NN	1.2/1.8
80	0.6/0.6	6.0/6.0	NN/NN	NN/NN	NN/NN	2.2/2.8
90	0.8/0.8	10.6/10.6	NN/NN	NN/NN	1.9/3.2	3.3/3.8
100	1.0/1.0	15.1/15.1	24.0/24.0	NN/NN	6.3/12.2	4.3/4.8

The left side of "/" is the bottleneck level for time period 1, and the right side of "/" is the bottleneck level for time period 2. NN = unnecessary.

TABLE 5 Necessity test of single condition of QCA method in each period.

Conditional variable	Time Slot 1		Time Slot 2	
	Consistency	Coverage	Consistency	Coverage
Food science education and technology R&D	1.00	1.00	0.664	0.663
~Food science education and technology R&D	0.250	0.249	0.420	0.353
Food safety testing	0.780	0.785	0.714	0.729
~Food safety testing	0.336	0.332	0.384	0.317
Green production momentum for enterprises	0.707	0.719	0.672	0.689
~Green production momentum for enterprises	0.385	0.378	0.418	0.344
Government special fiscal support	0.761	0.762	0.662	0.645
~Government special fiscal support	0.355	0.353	0.431	0.370
Energy consumption	0.767	0.770	0.667	0.629
~Energy consumption	0.372	0.369	0.453	0.401
Waste disposal	0.810	0.824	0.666	0.637
~Waste disposal	0.353	0.345	0.451	0.394

Consumption, and Food Safety Testing) have minimum thresholds necessary to achieve this goal.

4.2 Comprehensive configuration analysis

Ragin (2014) posits that prerequisites for specific outcomes may be categorized as core or non-core elements based on their essentiality. A prerequisite is deemed core if it appears in both intermediate and simplified solutions; it is non-core if present only in the intermediate solution and absent from the simplified one. The primary distinction lies in the degree of association with the specific outcome. Following Ragin and Fiss's symbolic notation: a solid circle (●) denotes the presence of either a core or peripheral condition, while a split circle (⊗) indicates the absence of either a core or peripheral condition (● = core condition present; ⊗ = core condition absent; • = peripheral condition present; ⊗ = peripheral condition absent), while blank circles denote conditions that may or may not be present (Fiss et al., 2014). In accordance with the aforementioned usage criteria, the results of the prerequisite condition configurations for green technological innovation efficiency in the food industry across two periods (Periods 1 and Periods 2) –including the original coverage, unique coverage, consistency, overall coverage, and overall consistency for each configuration –are detailed in Table 6. The presence or absence of core/peripheral conditions for the six prerequisites across the technological, organizational, and environmental dimensions within different configurations is clearly annotated.

1 Time Slot 1 configuration analysis

① Enterprise green production momentum–energy consumption-driven (SIa)

Within the SIa framework, the core configuration conditions for high efficiency in green technological innovation in food enterprises comprise corporate green production momentum and stable energy consumption. Peripheral enabling conditions include specialized food education and technological R&D, alongside food safety inspection. The consistency of this configuration pathway reaches 0.867. This indicates that even when specialized government financial support proves ineffective and waste disposal facilities are lacking, enterprises can still achieve high green technological innovation efficiency provided they possess core support and peripheral safeguards. The influence of specialized government financial support and waste disposal facilities is relatively weak in this context. Theoretically, regions with advanced economies and robust industrial foundations are better positioned to establish such configurations. These areas feature mature food industries where enterprises' endogenous demand for green transformation generates strong production momentum. Well-developed industrial ecosystems ensure stable energy supply, while high-quality educational resources and research capabilities provide talent and technical support, creating a virtuous cycle of 'innovation foundations–support systems'. Ten provinces, including Shanghai and Guangdong, align with this mechanism (see Table 7). They predominantly achieve this by implementing high-quality development plans for the food industry, establishing a 'policy guidance-technical support-collaborative innovation' framework, and focusing on the dual objectives of green transformation and security assurance. This approach strengthens end-to-end technical support and low-carbon production bench marking. Concurrently, robust green production momentum, stable energy supply, and educational R&D, alongside safety inspection safeguards within the food sector, collectively propel regional food enterprises towards high efficiency in green technological innovation.

② Enterprise green production momentum – waste treatment-driven model (SIb)

TABLE 6 Configuration results of each period.

Conditions		Time Slot 1				Time Slot 2			
		SIa	SIb	S2	S3	HI	H2	H3	H4
Technical level	Food science education and technology R&D	•		•	●	●		•	⊗
	Food safety testing	•	•	●	●	●	•	●	●
Organizational level	Green production momentum for enterprises	●	●	●	●	●	●	•	●
	Government special fiscal support		⊗	●	●		●	⊗	●
Environmental level	Energy consumption	●	⊗		●	⊗	●	●	●
	Waste disposal	⊗	●	•	•	⊗	⊗	●	⊗
Original coverage	0.171	0.162	0.130	1.162	0.132	0.090	0.090	0.129	0.171
Unique coverage	0.055	0.050	0.018	0.026	0.058	0.012	0.022	0.054	0.055
Consistency	0.857	0.867	0.846	0.849	0.871	0.801	0.802	0.852	0.857
Overall coverage rate			0.724				0.244		
Overall consistency			0.848				0.806		

●, core condition present; ⊗, core condition missing; •, edge condition present; ⊗, edge condition missing.

TABLE 7 Provinces and cities belonging to each period.

Configuration	Time Slot 1	Configuration	Time Slot 2
SIa	Shanghai, Guangdong, Beijing, Sichuan, Fujian, Chongqing, Hunan, Tianjin, Zhejiang, Liaoning	H1	Shanghai, Beijing, Zhejiang, Hunan
SIb	Shanghai, Beijing, Hunan, Guangdong, Sichuan, Zhejiang	H2	Inner Mongolia, Shanxi, Yunnan
S2	Jiangsu, Zhejiang, Shanghai, Guangdong, Shandong, Henan	H3	Inner Mongolia, Yunnan
S3	Beijing, Shanxi, Shanghai, Jiangsu, Zhejiang, Guangdong	H4	Shanxi

Under the SIb configuration, the core conditions for food enterprises to achieve high green technological innovation efficiency (configuration consistency = 0.846) are the enterprise's green production momentum and waste treatment capacity, with food safety testing serving as a peripheral condition. Even when specialized food education and technological R&D fail to exert significant influence, and despite the absence of dedicated government financial support and energy consumption conditions, food enterprises possessing core support and peripheral coordination can still achieve high innovation efficiency. The factors as mentioned above that do not exert significant influence have a relatively weaker impact on innovation efficiency. Theoretically, regions like Shanghai and Beijing—where industrial upgrading demands are urgent and environmental regulations stringent—are more conducive to such configurations. These areas feature concentrated food-industry production, which generates waste-disposal needs that spur the development of efficient resource recovery technologies. Simultaneously, safety standards in consumer markets drive refinement of the testing system. Enterprises spontaneously cultivate green production momentum to align with developmental demands, forming an endogenous 'demand-driven, capability-supported' mechanism. Specifically, robust green production momentum provides directional guidance for innovation; efficient waste treatment reduces environmental costs while supplying raw materials and experimental scenarios for R&D; and food safety testing optimizes the ecosystem to ensure innovation implementation. Shanghai, Beijing, Hunan, Guangdong, Sichuan, and Zhejiang exemplify this model (see Table 7). These provinces have generally established specialized plans and management measures for waste recycling, constructing a synergistic 'waste utilization-safety control' model. They strengthen end-to-end oversight and the application of safety-grade technologies, ultimately achieving high efficiency in green technological innovation through the coordination of core and peripheral conditions.

③ Food safety testing – enterprise green production momentum – enterprise green production momentum-driven (S2)

In Configuration S2, the core conditions for food enterprises to achieve high green technological innovation efficiency (consistency = 0.849) are fully competitive food safety testing and robust corporate momentum for green production. Peripheral conditions include specialized food education and technological R&D, alongside waste treatment. Even where energy consumption plays no significant role, enterprises can still attain high innovation efficiency provided they possess dual core support, peripheral synergistic coordination, and leverage high-intensity green fiscal policy guidance. Theoretically, regions like Jiangsu and Shandong—characterized by large-scale food industries and high marketization—are primed for such configurations. These areas serve as both core production hubs and consumption centers, where intense market demand for food safety drives competitive upgrades in testing. Their substantial industrial scale fosters endogenous green transformation momentum, while local governments frequently bolster green fiscal support to accelerate industrial upgrading, creating a 'market-driven, policy-empowered' development ecosystem. Specifically, competition in food safety testing and the momentum in green production constitute a multi-faceted innovation driver. Green finance provides financial and policy safeguards, while the integration of food education R&D with waste treatment solidifies talent reserves and practical platforms. These three elements synergistically enhance innovation efficiency. Six provinces including Jiangsu, Zhejiang, and Shanghai exemplify this mechanism (see Table 7). Guided by industrial planning, they establish R&D and testing support systems through core technology breakthroughs and innovation platforms, effectively driving corporate production transformation and safety management upgrades.

④ Integrated drive configuration (S3)

The configuration of S3 exhibits multi-factor synergistic driving characteristics, with core conditions comprising specialized food education and technological R&D, food safety testing, corporate green production momentum, dedicated government financial support, and energy consumption. Peripheral conditions involve waste treatment. This configuration pathway demonstrates a consistency coefficient of 0.871. Food enterprises meeting these conditions not only achieve high efficiency in green technological innovation but are also better positioned to elevate their innovation levels further. This implies that when enterprises possess sufficient educational R&D investment, a competitive testing environment, robust green production momentum, substantial fiscal support, stable energy consumption as core underpinnings, and efficient waste disposal as peripheral linkage, they can sustainably enhance innovation efficacy without additional conditions. Each element forms an efficient synergistic support system. Theoretically, economically advanced regions with well-planned industries—such as Beijing and Shanghai—are predisposed to such configurations. These areas prioritize high-quality food industry development by bolstering innovation funding through fiscal policies, cultivating R&D talent via premium educational resources, and fostering competitive testing environments through stringent market oversight. This creates a comprehensive 'policy-resource-market' driving mechanism. Specifically: educational R&D provides talent and technological foundations; food safety testing establishes quality and compliance benchmarks; corporate green initiatives ensure innovation implementation; fiscal support resolves funding constraints; stable energy supplies guarantee operational continuity; and waste treatment converts innovation outputs into resource value. Six provinces including Beijing and Shanxi exemplify this approach (see Table 7). Through food industry development plans, they establish coordinated systems integrating 'technological R&D – safety oversight–policy support', defining tasks such as cultivating green factories and establishing testing centers. This creates robust policy and resource support mechanisms that drive sustained innovation advancement.

2 Time Slot 2 configuration analysis.

① Food science education and technology R&D-food safety testing-enterprise green production momentum-driven (H1)

Under configuration H1, the core conditions enabling food enterprises to achieve high green technological innovation efficiency (consistency = 0.801) are specialized food education and technological R&D, food safety inspection, and corporate green production momentum. Government-specific fiscal support, energy consumption, and waste disposal are not key conditions and exert relatively weak influence. Even when the latter three factors fail to play a significant role, food enterprises with core support can still attain high innovation efficiency. Theoretically, regions with high marketization and mature industrial ecosystems—such as Shanghai and Beijing—are predisposed to such configurations. In these areas, intense competition among food enterprises fosters strong endogenous demand for green innovation. Concurrently, robust vocational education systems and advanced regulatory technologies enable firms to rely primarily on internal talent and technological reserves rather than external financial support, establishing a development model characterized by endogenous drivers supplemented by external support. Specifically, specialized food education and R&D lay the knowledge foundation and talent base for innovation; food safety testing provides safeguards through technological innovation and commercialization; while enterprises' green production momentum offers sustained impetus and application scenarios for innovation implementation. Together, these three elements synergistically construct an endogenous-driven innovation system. Shanghai, Beijing, Zhejiang and Hunan exemplify this approach (see Table 7). Through policies such as advancing vocational education, establishing innovative food safety supervision models and forming industry-education integration consortia, these provinces achieve precise alignment among talent cultivation, safety testing and corporate production, thereby significantly enhancing the efficiency of green technological innovation.

② Enterprise green production momentum–government specialized financial support – energy consumption-driven (H2)

In Configuration H2, the core conditions enabling food enterprises to achieve high green technological innovation efficiency (consistency = 0.802) are enterprise green production momentum, dedicated government fiscal support, and energy consumption. Peripheral conditions include food safety inspection, while food-specific education and technological R&D, along with waste treatment, exert limited influence. This indicates that even when the latter two factors fail to play a substantive role, enterprises can still realize high innovation efficiency through core support and peripheral synergy. Theoretically, regions like Inner Mongolia, Shanxi, and Yunnan—which possess strong energy endowments but relatively weak food industry R&D foundations—are prone to such configurations (see Table 7). These provinces leverage abundant energy resources to ensure production continuity while requiring targeted government fiscal intervention to drive green transformation in the food sector, forming a distinctive pathway characterized by 'policy underpinning + energy support + production-driven momentum'. Specifically: Three provinces, including Inner Mongolia, have leveraged food industry planning as a catalyst. They setting green factory development targets, offered substantial fiscal subsidies, and establishing clean energy usage quotas. By strengthening the linkage between 'enterprise self-inspection and regulatory testing, 'they have ultimately enabled synergy between policy support, energy optimization, and production-driven mechanisms, thereby enhancing the efficiency of green technological innovation.

③ Food safety testing-government specialized financial support-waste treatment-driven (H3)

In Configuration H3, the core conditions enabling food enterprises to achieve high green technological innovation efficiency in (consistency = 0.852) are competition-oriented food safety testing and effective waste-treatment capability. Peripheral conditions include specialized food education and technological R&D, alongside corporate green production momentum. The role of dedicated government financial support limited influence. This indicates that even without robust fiscal backing, and with peripheral conditions serving only an auxiliary role, food enterprises leveraging core support and peripheral synergy can still attain high innovation efficiency. Theoretically, Inner Mongolia and Yunnan—central agricultural and livestock processing provinces—generate substantial processing waste with urgent environmental disposal needs, yet face limited local fiscal support. This has fostered a configuration centered on leveraging inherent resource endowments and prioritizing breakthroughs in core processes: achieving environmental and economic gains through waste resource recovery, ensuring product quality through stringent testing, and reducing fiscal dependence. Specifically, food safety testing establishes a quality compliance foundation for innovation while clarifying its direction; waste treatment generates value through resource recovery, providing practical scenarios and circular carriers; peripheral education and R&D cultivate foundational talent, and corporate production momentum offers auxiliary drive. These four elements operate in synergy to enhance effectiveness. Inner Mongolia and Yunnan exemplify this approach (see Table 7). Both regions have increased waste-utilization rates and safety controls through schemes for recycling agricultural and livestock processing waste, establishing testing standards for recycled products, and developing a three-tier testing network. This has fostered an integrated ecosystem of 'waste utilization and safety assurance'.

④ Food safety testing – corporate green production momentum – government specialized financial support – energy consumption-driven (H4)

The H4 configuration exhibits multi-core synergistic driving pattern, with its core conditions being: highly-level food safety testing, robust corporate green production momentum, substantial government-specific fiscal support, and stable energy consumption. Food-specific education and technological R&D, alongside waste treatment, are do not serve as core conditions (exerting weaker influence). Food enterprises aligning with this pathway (consistency = 0.857) can achieve high green technological innovation efficiency without additional prerequisites, as the core conditions have already formed an self-sustaining synergistic system. Theoretically, Shanxi—a food industry transformation region with exceptional energy endowment—is suitable for developing this configurations (see Table 7)—its abundant energy resources (particularly clean energy potential) directly safeguard production continuity, local governments intensify fiscal inclination to advance green upgrades in traditional industries, while the food market's rigid demand for safety compels improvements in testing systems. This forms an endogenous development logic of 'energy support + policy drive + market traction', without excessive reliance on education/R&D or waste treatment segments. Specifically, food safety testing provides technical support and human resources for enhancing enterprise production momentum, while enterprises' green production capabilities lay the economic foundation for optimizing testing and implementing fiscal policies. Government-specific funding reduce capital barriers and guides resource aggregation, and stable energy consumption ensures continuous advancement throughout the innovation process. These four elements interact and mutually reinforce one another. Shanxi Province exemplifies this approach. Guided by its food industry planning, it has established a comprehensive innovation support system through: setting targets for cultivating green factories; providing dedicated subsidies; defining clean energy objectives; and implementing a three-level self-inspection mechanism. This system operates as a operation cycle of 'policy support–energy optimization– production drive–inspection assurance'.

To visually present the spatial distribution and temporal evolution of green technological innovation performance in China's food industry across provinces and municipalities, analysis is conducted based on the visualization results from Time Slot 1 (see Figure 2) and Time Slot 2 (see Figure 3).

In Time Slot 1 (see Figure 2), the eastern coastal regions developed a multi-driver development pattern. The core clusters of the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta—represented by Shanghai, Guangdong, and Beijing, respectively—showcased distinct configuration drivers: enterprise green production momentum-energy consumption driven, enterprise green production momentum-waste treatment driven, food safety testing-enterprise green production momentum-enterprise green production momentum driven, and comprehensive driven configurations. Beijing optimized its energy supply structure through planning, Guangdong established a solid waste treatment system, Shanghai streamlined technology transfer chains, and Jiangsu advanced multi-dimensional policy coordination, making them exemplary regions for distinct configurations. Central and western provinces like Sichuan, Chongqing, and Hunan belonged to either SIa or SIb configurations, leveraging local advantages to integrate into regional networks but failing to achieve fully factor-driven development.

In Time Slot 2 (see Figure 3), the eastern coastal regions deepened their talent- and economy-driven development. Shanghai, Beijing, Zhejiang, and Hunan formed a model driven by specialized food education and technological R&D, food safety inspection, and corporate green production momentum. Through industry-education integration, they strengthened the closed-loop of "educational reserves-scientific research conversion-economic reinvestment," marking an upgrade from factor-driven to innovation-driven growth. Meanwhile, the central and western regions rose through energy-and finance-driven development. Inner Mongolia, Shanxi, and Yunnan have formed a model driven by corporate green production momentum, government exceptional fiscal support, and energy consumption to facilitate the transformation of resource-based regions. Inner Mongolia and Yunnan have adopted a model driven by food safety testing, government exceptional fiscal support, and waste treatment, focusing on circular economy technology R&D. Shanxi stands as the only region meeting all four core conditions—food safety testing, corporate green production momentum, government exceptional fiscal support, and waste treatment—and is advancing deep transformation through its carbon peak plan.

Cross-period comparisons reveal that Time Slot 1 characterized by multi-configuration clusters along the eastern coast, forming the 'Yangtze River Delta-Pearl River Delta-Beijing-Tianjin-Hebei' innovation triangle. In Time Slot 2, central and western regions activated distinctive pathways through energy and fiscal policies, presenting a dual-engine pattern of 'deepening in the east and rising

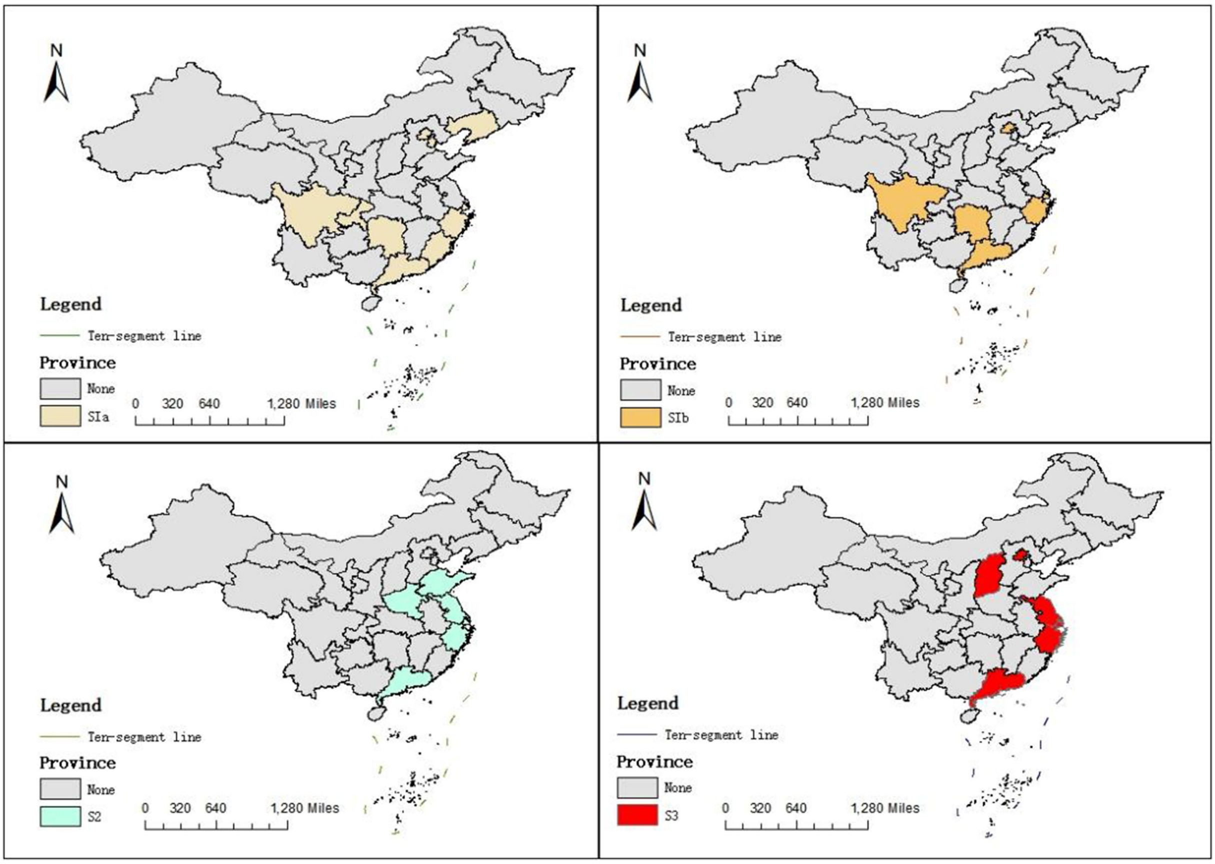

FIGURE 2
Provinces and municipalities corresponding to time slot 1 configuration.

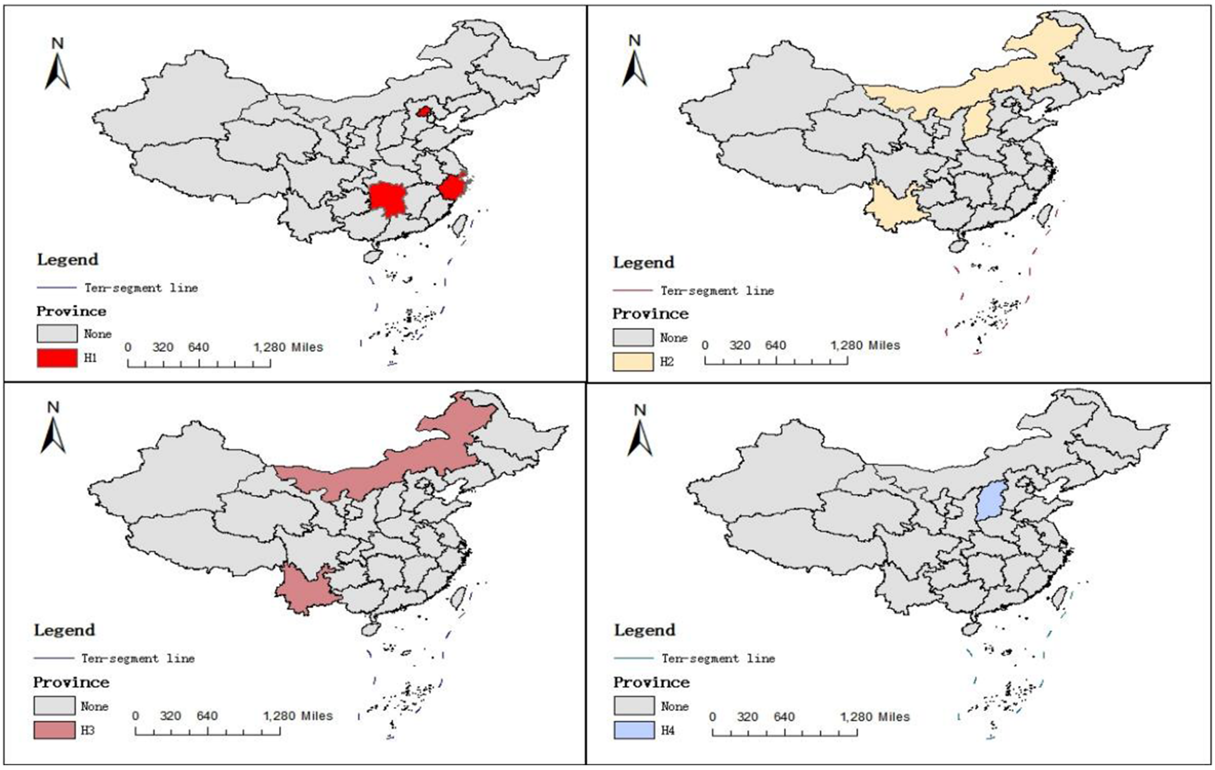

FIGURE 3
Provinces and municipalities corresponding to the second time slot configuration.

in the center-west'. Visual analysis indicates that eastern regions transitioned from a two-dimensional driver (economic-energy/waste management) to a three-dimensional synergy of education-testing-economic drivers. In contrast central and western regions shifted from peripheral participation to core drivers of energy-fiscal-technology. Driving factors evolved from unipolar dominance to a multi-faceted combination of 'education-testing-policy-energy', reflecting regional policy divergences: eastern strategies prioritizing commercialization and industry-education integration, and central-western approaches focusing on energy transition and resource recycling. Ultimately, this reveals the evolutionary logic of driving mechanisms across different periods—shifting from single-factor to multi-factor approaches and from eastern concentration to cross-regional coordination—providing visual evidence for differentiated policy formulation.

4.3 Robustness testing process

When conducting robustness tests in this paper, specific parameters were set to ensure the reliability of results. The case-frequency threshold was set at 2, focusing on condition combinations that appeared ≥2 times to identify prevalent configuration patterns and avoid interference from low-frequency cases. The consistency level was set at 0.77 to ensure high consistency in configuration interpretation outcomes. The PRI value exceeds 0.5, serving as a key indicator of the stability and validity of configuration outcomes. Higher values denote greater robustness, thereby enhancing the quality and reliability of research findings. As illustrated in Table 8.

First, the original consistency was increased from 0.75 to 0.77, resulting in a largely consistent configuration.

Second, after adjusting the original consistency threshold, the overall consistency of conditions in Time Slot 1 and Time Slot 2 remained highly stable compared to the original coverage values, with overall consistency values of 0.893 and 0.854, respectively. The consistency results for both Time Slot 1 and Time Slot 2 exceeded those in Table 6, further confirming the robustness of the model developed in this study.

Finally, the adopted conditions configurations consistently explains the efficiency of green technological innovation in the food industry across different time periods. At the technological level, food-specific education and technology development, along with food safety testing, demonstrate strong consistency, indicating that food-specific education and technology R&D, coupled with food safety testing, play a decisive role in enhancing the performance of green technological innovation in the food industry. At the organizational level, corporate green production momentum exerts a significant positive effect on the performance of green technological innovation in the food industry. At the environmental level, energy consumption contributes positively to in the efficiency of green technological innovation within the food industry. The combination consistently explains the performance of green technological innovation in the food industry across multiple time phases. Therefore, the model developed in this study is robust.

In summary, during the robustness testing process, all consistency results obtained met the testing requirements, thereby validating the robustness of the test outcomes.

TABLE 8 Robustness test.

Conditions		Time Slot 1		Time Slot 2	
		SIa	SIb	H1	H2
Technical level	Food science education and technology R&D	•		●	
	Food safety testing	•	•	●	•
Organizational level	Green production momentum for enterprises	●	●	●	●
	Government special fiscal support		⊗		●
Environmental level	Energy consumption	●	⊗	⊗	●
	Waste Disposal	⊗	●	⊗	⊗
	Original coverage	0.162	0.153	0.125	0.085
	Unique coverage	0.052	0.047	0.055	0.011
	Consistency	0.814	0.823	0.827	0.760
	Overall coverage rate	0.687		0.231	
	Overall consistency	0.893		0.854	

5 Discussion

5.1 Theoretical contributions

5.1.1 The logical framework supporting policy formulation

A prevalent cognitive bias of 'single-factor dependence' exists in traditional food industry policy design. The root cause of this bias lies in the lack of systematic theoretical understanding of the mechanisms driving GTI performance. The multidimensional configuration framework—integrating technology, organization, environment, and food-safety elements—developed in this research provides core theoretical support for policy formulation. Findings from 30 provincial samples demonstrate that single variables do not drive high GTI performance in the food sector but emerges through synergistic coupling of technological R&D, organizational management, institutional environment, and food safety elements.

The 'configurational cognition' reflected in these theoretical conclusions departs from traditional policy reliance on singular tools such as capital investment and policy subsidies in traditional policy making, providing a theoretical basis for 'multi-factor synergistic action' in policy design. Concurrently, the dynamic evolution patterns of the GTI mechanism revealed by the theory—the 'driving force-energy' model from 2013 to 2017 and the 'R&D-inspection-driving force' configuration from 2018 to 2022—provide theoretical guidance for transitioning policy orientation from 'static planning' to 'stage-adaptive dynamic adjustment.' This enables policy interventions to align more closely with the intrinsic logic of industrial development.

5.1.2 The practical value of theory for industrial development

The dual objectives of 'low-carbon emission reduction' and 'safety assurance' in the food industry reflect a misalignment between the 'efficiency-first' and 'risk prevention' perspectives in traditional development models. This study reveals the synergistic mechanism linking specialized R&D, safety inspection, and green incentives, thereby constructing a theoretical logic that integrates these dual objectives: the energy-saving impact of green-technology R&D and the market trust value generated by establishing safety inspection systems form a complementary rather than antagonistic relationship within this theoretical framework.

This theoretical framework provides enterprises with practical guidance for resource integration—firms with different scales and resource endowments may select appropriate factor combination models based on the multi-pathway driven model revealed by the theory, thereby avoiding the practical pitfalls of prioritizing innovation over safety or emphasizing safety at the expense of transformation. Simultaneously, the theory's explicit articulation of synergistic factor value offers theoretical underpinnings for establishing dual-oriented 'safety-green' development standards within industries, thereby propelling high-quality industrial advancement.

5.1.3 Academic innovation in theoretical frameworks and research paradigms

By addressing the dual challenges of 'theoretical framework limitations' and 'single-method research paradigms' within GTI research in the food industry, this research achieves breakthroughs across both theoretical and methodological dimensions. Establishes a core academic contribution that integrates both theoretical advancement and methodological innovation.

At the theoretical framework level, this study integrates embeds food safety elements within the classical Technology-Organization-Environment (TOE) framework, constructing an extended 'TOE-S' framework tailored to the food industry. This expansion not only overcomes the limitations of traditional Resource-Based View (RBV) theory, which prioritizes internal resources while neglecting external safety constraints, and addresses the shortcomings in Strategic Management Theory (STM), which emphasizes competitive strategy while weakening interaction among elements. By demonstrating that food safety elements can synergistically drive Green Technology Innovation (GTI) through mechanisms such as 'market trust formation' and 'innovation process standardization', this research enriches the TOE framework's conceptually. It broadens its applicability within high-risk, heavily regulated industries offering for a theoretical model for green innovation studies in specific sectors.

At the research paradigm level, to support framework validation and theoretical expansion, this study integrates Necessary Condition Analysis (NCA) with fuzzy-set Qualitative Comparative Analysis (fsQCA), introducing a dynamic segmentation that constructs an integrated analytical paradigm of static-configuration and dynamic-evolution models. This paradigm not only overcomes cognitive limitations in traditional research—such as single-path attribution and static cross-sectional analysis—but also advances green-innovation studies by revealing configurational mechanisms and temporal evolution patterns affecting GTI performance. It promotes a shift from 'single-causal cognition' to 'configurational causal cognition' and from 'static description' to 'dynamic interpretation'. This methodological-theoretical synergy provides a replicable academic paradigm for subsequent GTI research in the food industry, enhancing theoretical depth and scientific rigor of studies in this field.

5.2 Practical implications

5.2.1 Optimize technological supply to establish a dual-objective coordination system

Focusing on the dual objectives of 'green technological innovation and food safety assurance', we shall increase targeted investment in areas such as green food processing technology, rapid safety testing techniques, and intelligent traceability systems. By interdisciplinary training programs should be developed and integrating industry standards to cultivate multi-skilled professionals, dedicated industry-academia-research funds should be established to advance collaborative breakthroughs in key technologies, and a closed-loop mechanism should be formed system for targeted talent placement and commercialization of outcomes, we shall ensure seamless alignment between technological R&D, talent deployment, and enterprise needs for safety management and green transformation.

5.2.2 Strengthen organizational support and enhance the regulatory mechanism for policy resources

Under government-led guidance, green technology R&D should be closely aligned to food safety standards. Incentives such as fiscal subsidies and additional tax deductions for R&D expenditure will be provided to relevant innovation projects, thereby reducing enterprises' dual innovation costs. A comprehensive service platform will be established, integrating standard databases, testing resources, and green financial products providing enterprises with one-stop support encompassing 'technology selection–testing and certification–funding matching'. A fiscal funding evaluation system will be implemented, linking fund utilization to food safety compliance performance and the effectiveness of technology implementation, to ensuring targeted financial empowerment.

5.2.3 Fostering an enabling environment to advance energy circularity and collaborative governance

Tailored clean energy substitution schemes should be implemented in accordance with the energy consumption characteristics of food processing. Enterprises adopting photovoltaic or hydroelectric power shall receive electricity price subsidies along with complementary energy consumption monitoring systems. The processing waste management cycle of 'segregated collection–safe disposal–high-value utilization' should be advanced, with mandatory resource recovery processes subject to food safety indicator testing. Public awareness campaigns should be strengthened on green food certification and traceability experiences to guide consumption and stimulate innovation. Establish reporting channels should be established for non-compliance to foster a collaborative governance framework involving government oversight, corporate innovation, and public participation.

6 Conclusion

Based on dual validation through Necessity Condition Analysis (NCA) and fuzzy set Qualitative Comparative Analysis (fsQCA), this study concludes that enhancing Green Technology Innovation (GTI) efficiency within the food industry cannot rely solely on the independent influence of any single dimension—technological, organizational, or environmental—but must instead depend on the synergistic interaction of multiple dimensions. This conclusion not only consolidates the empirical findings of this study but also provides multidimensional value at theoretical, practical, and research continuity dimensions.

At the theoretical level, this study addresses the limitations of 'single-factor determinism' prevalent in traditional green innovation research. By integrating key elements such as food safety inspections and specialized food education within the Technology-Organization-Environment (TOE) framework, and revealing a two-stage differentiated implementation mechanism—the first stage featuring an 'integration-driven' equivalent configuration and the second stage a composite configuration featuring 'food safety inspections—enterprise green production incentives—government specialized financial support—energy consumption drivers'—this study enriches the configuration research paradigm of GTI efficiency, offering a novel theoretical perspective on 'multi-factor synergy' to explain regional disparities in innovation efficiency.

At the practical level, this offers clear guidance for implementing targeted regional policies. Given that diverse combinations of factors can achieve equally effective GTI performance, local governments do not need to follow a single development model. Instead, they should leverage their unique resource endowments to reinforce key factor combinations: in regions with concentrated food industry clusters, dedicated fiscal support can be used to stimulate enterprises' motivation for green production; in areas rich in scientific research resources, collaboration with universities and research institutions can strengthen food safety inspection systems, ultimately forging differentiated innovation-driven development pathways.

From a prospective research perspective, the identified variations in GTI efficiency pathways provide crucial insights into dynamic mechanisms. Subsequent studies may focus on the evolutionary logic of factor combinations, delving into how external conditions—such as shifts in policy environments and technological iterations—influence the intensity of core factors' effects. This would refine the dynamic theoretical model of GTI efficiency, offering more forward-looking academic support for the industry's long-term green transition.

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/s.

Author contributions

XX: Funding acquisition, Supervision, Validation, Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Investigation, Methodology, Project administration, Formal analysis. WL: Data curation, Supervision, Validation, Writing – original draft, Writing – review & editing, Methodology, Project administration, Software. QX: Conceptualization, Investigation, Methodology, Validation, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study titled "Mechanisms Influencing Green Technology Innovation Efficiency in China's Food Industry: A TOE-Framework Perspective Guided by Food Safety Assurance" has received financial support from two funding sources, and all funds utilized for the research have been fully disclosed herein. Specifically, the research is supported by the National Social Science Foundation of China under Grant No. 24BGJ019. As a national-level funding agency, the National Social Science Foundation of China provides core theoretical and methodological underpinnings for this study, enabling in-depth exploration of the macro-level institutional mechanisms and policy contexts that affect green technology innovation in China's food industry. Additionally, this study has obtained funding from the Basic Research Project of Liaoning Provincial Department of Education under Grant No. LJKMR20220911. The Liaoning Provincial Department of Education, as a regional academic support institution, facilitates the collection of regional food industry data, conducts localized empirical analysis, and ensures the practical relevance of the research findings to the development of the food industry in specific provinces, thereby complementing the national-level research perspective.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1727846/full#supplementary-material

References

Ahmad, W., Sohail Jafar, R. M., Khan, N. R., Hameed, I., and Fatima, N. (2023). "Does green blogging affect consumer green behaviour? Moderating role of green psychology variable" in Entrepreneurship and green finance practices: Avenues for sustainable business start-ups in Asia (Leeds, England, United Kingdom: Emerald Publishing Limited), 183–192.

Batool, F., Alhidary, I. A., Boda, J. R., Alwadi, B. M., Khudoykulov, K., and Haseeb, M. (2025). Balancing sustainability and profitability: the financial effect of green innovation in Chinese high-pollution industries. *Sustainability* 17, 3610–3610. doi: 10.3390/SU17083610

Dong, L., and Qi, G. (2025). How embedded collaboration in food safety governance is achieved: a case study of Z agricultural enterprise. *World Agric.* 2, 81–92. doi: 10.13856/j.cn11-1097/s.2025.02.007

Dzwolak, W., and Anim, B. (2025). Barriers hindering maintenance of standardised HACCP-based food safety management systems in small polish food businesses. *Food Control* 168:110849–110849. doi: 10.1016/j.foodcont.2024.110849

Fei, W., Li, Y., and Yu, B. (2025). Digital economic development and food safety. *J. South China Agric. Univ.* 24, 92–104. doi: 10.7671/j.issn.1672-0202.2025.02.008

Fiss, P. C., Marx, A., and Rihoux, B. (2014). Getting QCA right. *Sociol. Methodol.* 44, 95–100. doi: 10.1177/0081175014542079

Gao, F. (2025). An overview of international food codex standards. *World Agric.* 5, 145–148. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdYGjiOEotBasq8MKUFrN1g1lhpZ6P6CxTs9zwQZCugt_WZc2QsFnlrO_YtqAWs5pfFn83nETkcqqMy62bSFyRzLPpp3od9-bJlCTNWXhE3ZSwCpf_P4krP0_fBmRvCmO9Q_FB2rmG2hrz7kkTGH1PEQORv-dqgVxi7pjqPdg-fTuw==&uniplatform=NZKPT&language=CHS

He, D., and Yu, Y. (2025). Research on blockchain-enabled digital governance of food safety from an information ecosystem perspective. *Res. Sci. Technol. Manag.* 45, 161–168. doi: 10.3969/j.issn.1000-7695.2025.5.017

Hong, C., Zhong, R., Xu, M., He, P., Mo, H., Qin, Y., et al. (2025). Interactions among food systems, climate change, and air pollution: a review. *Engineering* 44, 215–233. doi: 10.1016/J.ENG.2024.12.021

Hu, L. M., and Chen, T. K. (2025). Research on sustainable food literacy education talent cultivation. *Sustainability* 17:7172-7172. doi: 10.3390/SU17167172

Hu, G., Li, B., and Lai, J. (2025). The impact of environmental tax policies on artificial intelligence investment: evidence from Agri-food, food processing, and other industries. *Front. Sustain. Food Syst.* 9:1618551-1618551. doi: 10.3389/fsufs.2025.1618551

Hu, Y., and Wu, J. (2025). Party-led intelligent governance: elements and pathways for high-efficiency social governance—an FSQCA analysis of 43 food safety cases. *Macro Qual. Res.* 13, 105–118. doi: 10.13948/j.cnki.hgzlyj.2025.03.008

Jabeen, M., Jafar, R. M. S., and Li, Z. (2025). Leveraging metaverse technologies for a sustainable future: the role of knowledge management practices and technology readiness. *Technol. Soc.*:103122. doi: 10.1016/J.TECHSOC.2025.103122

Jafar, R. M. S., Jabeen, M., Hussain, S., Niu, B., Sham, R., and Al-Adwan, A. S. (2025). Cyber shopping beyond boundaries: the metaverse revolution in e-commerce and consumer behavior. *Hum. Behav. Emerg. Technol.* 1:5559234. Available online at: https://onlinelibrary.wiley.com/doi/full/10.1155/hbe2/5559234

Jafar, R. M. S., Rabnawaz, A., Hussain, S., Ahmed, W., and Zhuang, P. (2015). Aptitudes of Pakistani rice industry with respect to global trade. *Journal of Economics and Sustainable Development*, 6, 8–12. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdZY3NSV9MxgZYDsiLyA3gSKpPmrAVv5LpOuS1dNkYSpnB_bcFfWzByxQzLLITC2uZ8flCepgYDKhw5zyegoNcURJme5MIlr44rECJayNscTme6FQ6DGYAs752mzP1NDXwYrNCNbEtnBAHQO_OQ1BEHMrvUc3gB8JBZbIni3d0hKQja5b5SPDTVzrMprh7pJYoXCSvtim7FpZg==&uniplatform=NZKPT&language=CHS

Jiang, D., Jin, M., and Wei, Z. (2025). 'Price mark-up' or 'quality upgrade'? — the impact of China's food quality standards enhancement on aquatic product exports. *Ind. Econ. Rev.* 4, 19–39. doi: 10.19313/j.cnki.cn10-1223/f.20250616.002

Li, M., and Fu, P. (2023). The path to sustainability in green agricultural industry innovation practices: a case study from the perspective of 'external environment-grassroots strategy'. *Public Adm. Rev.* 16, 26–45+196. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdb6LXJO1aoEPNYXuB9e2SEWxBYWH5kmBOH9u2fsPGwLeRLeCfb-rCBdkUadBkpUbepWtaU5vy1fXgZD0b6tUW4oQUV3RixyyAm41kZuAxKP-FDvNSARw_r3DV0wdVvV_cviJRI6GsE8gqfkOvztFHGVZzPdpzIk0kmISCbn7KCHUw==&uniplatform=NZKPT&language=CHS

Lin, H., Guangxu, L., and Yingchun, F. (2023). Recent developments in biosensing strategies for the detection of small molecular contaminants to ensure food safety in aquaculture and fisheries. *Trends Food Sci. Technol.* 133, 15–27. doi: 10.1016/J.TIFS.2023.01.016

Liu, C., Wang, N., Liu, X. L., Zhang, Y. Y., and Liu, Y. G. (2024). An analytical overview of the composition and characteristics of China's food safety standards. *J. Sci. Food Agric.* 104, 3197–3205. doi: 10.1002/JSFA.13262

Liu, J., and Zhang, H. (2025). The impact of green technological innovation on green development: an empirical analysis at the prefecture-level city level in China. *J. Hubei Univ.* 52, 157–166. doi: 10.13793/j.cnki.42-1020/c.2025.04.019

Ma, J., Chen, J., and Zhao, Y. (2025). Research on digital gatekeepers and agricultural product quality and safety control mechanisms within the live-streaming e-commerce value chain. *Manag. World* 41, 175–198. doi: 10.19744/j.cnki.11-1235/f.2025.0054

Madilo, F., Kunadu, A., and Tano Debrah, K. (2024). Challenges with food safety adoption: a review. *J. Food Saf.* 44, 2–3. doi: 10.1111/jfs.13099

Mahmood, S., Iqbal, A., El-kenawy, E. S. M., Eid, M. M., Alhussan, A. A., and Sami Khafaga, D. (2025). The impact of green technology innovation, pro-environmental behavior and eco-design on green new product success: examine the moderating role of green corporate image. *Environ. Res. Commun.* 7:015028. doi: 10.1088/2515-7620/adaaca

Moran, A., McDonagh, M., O'Donovan, S., and Ryan, L. (2024). A qualitative investigation into the digital competencies and food sustainability knowledge employers require of graduates in the food industry across Europe. *Proceed. Nutr. Soc.* 83, E352–E352. doi: 10.1017/S0029665124005901

Ragin, C. C. (2008). Redesigning social inquiry: Fuzzy sets and beyond. Chicago: University of Chicago Press.

Ragin, C. C. (2014). The comparative method: moving beyond qualitative and quantitative strategies. Berkeley: University of California Press. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdZ7JCiWiYx1sheMeoBLvCyRGbrNXouf8NLGzvPiDhj2Y3BiuEsnvzHInJxDhUemOEfkG6_j_EggDYJZ01KS9iclDMaxpuOxHY_Wb-w0C4ZDElFie5bl0oZ8Aly8G918PVAHTjKjV0Vq_-TDiz_EBMSqR5eb_5cIqIwTT3GiCnhRsdTsdAl32G4tqCwBSfkSIBE=&uniplatform=NZKPT&language=CHS

Sanguinet, R. E., and García, G. B. D. F. (2023). Rural-urban linkages: regional financial business services' integration into Chilean Agri-food value chains. *Sustainability* 15, 6–7. doi: 10.3390/su151410863

Teng, C. (2023). Using the fsQCA approach to investigate factors affecting university students' satisfaction with online learning during the COVID-19 pandemic: a case from China. *Front. Psychol.* 14:1123774. doi: 10.3389/fpsyg.2023.1123774

Trusova, N. V., Metelenko, N. H., Danylyshyn, M. S., Nikitchenko, S. O., and Ogloblina, V. O. (2025). Circular green investments in the model of the development of financial potential of the food processing industry of Ukraine. *Food Human.*, 5, 5100763–5100763. doi: 10.1016/J.FOOHUM.2025.100763

Vialkova, E., Korshikova, E., and Fugaeva, A. (2024). Phytosorbents in wastewater treatment technologies: review. *Water* 16:2626-2626. doi: 10.3390/w16182626

Wang, J., Qiu, J., and Zhang, Y. (2023). Pathways for enhancing the coupling coordination degree of regional innovation chains driven by multiple factors: an fSQCA analysis under the TOE framework. *Sci. Technol. Progress Policy* 40, 34–44. doi: 10.6049/kjjbydc.2022080430

Wu, L., and Chen, Y. (2024). An evaluation study on the governance effectiveness of policy instruments in China's food safety risk management. *Acad. Forum* 47, 118–132. doi: 10.16524/j.45-1002.20240203.001

Xiaozhi, X., Yaxian, Z., Li, P., Manyin, L., Wenpeng, D., and Sheng, X. (2023). Exploring the food-energy-water nexus in China's national industries: insights from network structure and production disturbances. *Sustain. Prod. Consum.*, 43, 43377–43388. doi: 10.1016/j.spc.2023.11.013

Xin, L. (2025). Digital industry agglomeration, technological innovation and urban green economic efficiency. *Statist. Decision Making* 41, 96–100. doi: 10.13546/j.cnki.tjyjc.2025.12.016

Yao, M., and Pan, J. (2025). Industrial green innovation efficiency: spatial patterns, evolution, and convergence in the Yangtze River Economic Belt. *Sustainability* 17:4880-4880. doi: 10.3390/SU17114880

Yuan, Z., Li, J., Feng, Z., and Liu, X. (2025). Food productivity, green energy and land resources: a critical perspective of the BRICS economic food production industry. *Land Degrad. Dev.* 36, 1736–1749. doi: 10.1002/ldr.5461

Zhang, B., Ma, R., and Wu, T. (2024). Digital technology empowering the modernisation of China's food safety: theoretical logic, practical challenges and exploratory pathways. *J. Humanit.* 7, 116–127. doi: 10.15895/j.cnki.rwzz.2024.07.008

Zhang, X., Xiong, B., Xu, L., and Li, C. (2025). Commercial credit financing and food safety. *Econ. Theory Manage.* 45, 103–118. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdYZf2x_yXefKbHeqlZy6XjzYZPX1skGOKZR8x15TkUkfPUiNbLjKojlTlGeN2D6tB3DH8y7tmGwyxOGvHIl8vSLvNugJ0_B2aDgYkOMxHdmKszR8MT7SuSgLLjnytn2_b_ZS0gEg8pdKZcbONjTdIsWpU6ls6dOawQKOEXwhHktgw==&uniplatform=NZKPT&language=CHS

Zhou, X., Jia, M., and Zhao, X. (2023). Evolutionary game dynamics and empirical analysis of green finance promoting corporate green technological innovation. *China Industr. Econ.* 6, 43–61. doi: 10.19581/j.cnki.ciejournal.2023.06.002

Zhu, Z., Li, M., and Ning, K. (2025). Labour relations, institutional environment and food safety in online catering services: the interests linkage between delivery personnel and platforms and their 'whistleblowing' behaviour [J/OL]. *Consumer Econ.*, 1–18. Available online at: https://kns.cnki.net/kcms2/article/abstract?v=8Znygsi0fdZJZQ1LqnTFMLOGapsDcRlsiUYSB5OYyBvm0jHqWOSwGG1vVqNNrIO1ta27P-Pd2gC8BdwgZcA7JQGvpzhFRNnKZsuk14Js5yD2JLK-cl_dtZerdX9QrdBtFQ1vbS_CzBKkIqcAnkG6cnfQcW9kfQwyyX3a-0cPQGY9Zpycc4F7dg==&uniplatform=NZKPT&language=CHS

Zhu, M., Yang, G., Jiang, Y., and Wang, X. (2023). Agent-based modeling for water–energy–food nexus and its application in Ningdong energy and chemical base. *Sustainability* 15, 7–8. doi: 10.3390/su151411428

Zou, B., Chen, Y., Mishra, A. K., and Hirsch, S. (2024). Agricultural mechanization and the performance of the local Chinese economy. *Food Policy* 125:125102648. doi: 10.1016/j.foodpol.2024.102648