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Industrial digital-green coupling transition in China: agricultural insights and broader implications

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This study examines the coupling relationship between digital transformation and green development in Chinese listed companies, with a particular focus on the agriculture and food industry from 2009 to 2022. Using principal component analysis (PCA) combined with TOPSIS and FEMA, the paper constructs a multidimensional measurement model to assess the coupling coordination degree between digital and green systems. The results reveal that overall coupling has significantly improved over time, especially in the service industry, while the agriculture sector shows a slower but upward trend due to digital infrastructure constraints. Digital transformation notably enhances green innovation and environmental performance, but challenges remain, such as strategic green innovation behaviors and financial policy gaps. The study highlights the need for targeted policies to bridge digital divides and promote substantive green innovation in agriculture and food sectors. These findings provide valuable insights for policymakers and corporate leaders aiming to accelerate the dual digital-green transformation in China's industrial sectors.

KEYWORDS

agri-food industry digital transformation, green development, coupling degree, TOPSIS method, digital economy, environmental performance

1 Introduction and literature review

1.1 Introduction

In recent years, with the rapid development of digital technologies, such as artificial intelligence, big data, cloud computing, blockchain, etc., as well as the increasingly severe environmental problems around the world, governments have taken the promotion of green and low-carbon transformation and the development of the digital economy as an important path for high-quality economic transformation. Especially in China, digital transformation and green development have become important factors in promoting the optimisation of financial structure and enhancing national competitiveness. The report of the 20th National Congress of the Communist Party of China (CPC) explicitly proposed "Accelerating the development of the digital economy and promoting the deep integration of the digital economy and the real economy", and the Decision on Further Deepening Reforms in a Comprehensive Way and Promoting Modernization of the Chinese Style adopted by the Third Plenum of the 20th CPC Central Committee also put forward the requirement of "improving the mechanism of green and low-carbon development", which points out the direction of the dual transformation for the development of enterprises (State Council of the People's Republic of China, 2023).

In this paper, the synergistic promotion of enterprise digital transformation and greening development has become an important topic for theoretical research and practical exploration. On the one hand, the rapid application of digital technology is gradually becoming a new driving force for China's economic growth (Xue et al., 2022), and plays a key role in promoting the transformation and upgrading of traditional industries and promoting the innovation of new industries and new business models (Li, 2020). On the other hand, green and low-carbon development has become a global consensus, and General Secretary emphasized at the National Conference on Ecological Environmental Protection in July 2023 that it is necessary to "vigorously develop green finance, and promote the innovation of ecological environment-oriented development models and investment and financing models" (Ministry of Ecology and Environment of the People's Republic of China, 2023). Under these dual pressures, companies need to synchronize their green development with digital transformation to cope with fierce market competition and improve environmental performance (Chen and Hao, 2022).

Existing research shows that there is a close link between enterprise digital transformation and enterprise environmental performance. Empirical studies have found that digital transformation can significantly improve the environmental performance and green innovation level of enterprises, and technologies such as artificial intelligence, big data, cloud computing, and their practical applications have a positive impact on the environmental performance of enterprises (Xu Q. et al., 2023). Zhao et al. (2024) and Xu J. et al. (2023) research has pointed out that the digital transformation of enterprises can significantly reduce pollutant emissions and promote innovation in eco-processes, products and management of enterprises. Zhao Q. et al. (2023) found that enterprise digital transformation indirectly contributes to ESG performance by promoting enterprise structural optimisation, improving green innovation capacity and reducing inefficient investment.

In this complex context, accurately measuring the coupling relationship between corporate digitalisation and greening is crucial for understanding the dual transformation process. Currently, the measurement of digital transformation is mainly done through textual analysis of corporate annual reports to extract the frequency of keywords of digital technologies, including artificial intelligence, big data, and cloud computing (Gómez-Cruz et al., 2022). The level of green development, on the other hand, is mainly measured through corporate environmental performance (e.g., ESG environmental rating) and green innovation indicators (e.g., green patent applications) (Xu et al., 2021). However, there is still a relative lack of systematic measurement studies on the coupling relationship between the two, especially in terms of differentiated analyses at the level of different industry types and firms. This paper aims to fill this research gap by establishing a scientific measurement system to analyse the coupling relationship between digital transformation and the greening development process of Chinese listed enterprises. Specifically, this paper innovatively adopts the multivariate measurement method of principal component analysis (PCA) as the main method, with TOPSIS and FEMA as auxiliary methods, to comprehensively analyse the data of Chinese listed enterprises from 2009 to 2022. The research design is divided into three levels: the first level examines the differences in the degree of number-green coupling between each industry (first, second and third) and the overall; the second level compares the degree of number-green coupling between the manufacturing industry and the whole industry; and the third level analyzes in detail the differences in the number-green coupling indexes between each classification of listed companies in the manufacturing industry (C09-C31) and the overall PCA. This paper not only helps to reveal the interaction mechanism and influencing factors of digitization and greening in enterprise transformation, but also provides more accurate decision support for policymakers and helps enterprises realize the synergistic development of digitization and greening. Meanwhile, the results of the study will also provide an empirical basis for further improving the relevant theoretical framework and optimizing enterprise transformation strategies, which is of great theoretical value and practical significance for promoting the high-quality development of China's economy.

However, the relationship between digitization and greening is not a simple linear facilitation, but there are complex interaction mechanisms. Research suggests that firms may engage in strategic green innovation behavior when there are information barriers between government and business, and lagging innovation regulatory policies (Qiu et al., 2020). Specifically, firms may use digitalisation to ostensibly increase the number of green innovations, but these innovations do not improve environmental performance. In addition, while policy instruments such as green bonds provide financial support for firms' green transformation, excessive financial incentives may distort the role of firms' digital transformation in promoting substantive green innovations (Xiang et al., 2022), and make firms more inclined to engage in lower-quality strategic innovations to obtain policy subsidies (Liu et al., 2019). Different types of enterprises also show significant differences in the interaction between digitalisation and greening. From the perspective of ownership, the digital transformation of SOEs contributes more significantly to environmental performance, and non-SOEs are more inclined to adopt strategic green innovation behaviors, while SOEs are more inclined to substantive green innovation under the financial incentives of green bonds (Yu et al., 2022). In terms of industry type, manufacturing enterprises and non-heavily polluted industries are more inclined to strategic green innovation, while non-manufacturing enterprises and heavily polluted industries are more inclined to substantive green innovation (Fan et al., 2024). Differences in digitization levels between industries are also significant, with information transmission software and information technology services, finance, and scientific research and technology services having the highest digitization levels; from the perspective of the three industries, the digitization level of the service industry is about 35%, the industry is about 20%, and the agriculture is about 9% (China Academy of Information and Communication Research, 2022).

1.2 Literature review

1. Connotation of digitization and greening, and interaction mechanism:

Digital transformation not only covers the enterprise's adoption of new-generation information technology such as artificial intelligence, big data, cloud computing, blockchain, etc., but also involves an all-around reconstruction of the enterprise's organizational form, business model and management processes (Kotarba, 2018). Digitalization can be deconstructed from the dimensions of digital technology, data elements, digital industry, and production and lifestyle. Enterprises utilizing digital technology can effectively reduce operating costs, improve operational efficiency, and have a profound impact on internal management and external transactions. Enterprise greening refers to the reduction of pollutant emissions and improvement of environmental performance through the adoption of environmentally friendly technologies, green innovation and strict environmental management while realizing economic benefits (Fernandez, 2022). Currently, ESG ratings or environmental scores are widely used as indicators of corporate environmental performance (Xu et al., 2021), while corporate green innovations, such as green patent applications, are also important means to improve environmental performance (Huang et al., 2023). Existing studies generally point to a positive interaction between digital transformation and corporate greening. Digital transformation can promote green innovation within enterprises by reducing management costs, easing budget constraints, and promoting human capital accumulation, and at the same time improve environmental governance using digital monitoring and information disclosure, which in turn improves the environmental performance of enterprises (Wang et al., 2024; Abbas and Najam, 2024; Chen and Hao, 2022). In addition, information barriers in the digitization process and lagging innovation regulatory policies may make firms more inclined to adopt strategic green innovation (Akhtar et al., 2024), which constitutes one of the moderating mechanisms of the interaction between the two.

2. Digitization and greening measurement methodology:

To comprehensively measure the degree of coupling between enterprise digitization and greening, the existing literature and empirical studies use a variety of measurement and statistical methods. Existing literature adopts keyword statistics for digitization level, and constructs indicators by using Python crawler technology to count the word frequency of keywords such as "artificial intelligence", "big data", "cloud computing", "blockchain", etc., in the annual reports of enterprises, "big data", "cloud computing", "blockchain" and other keywords in the enterprise annual report by using Python crawler technology to construct indicators by counting the word frequency of these keywords (Gómez-Cruz et al., 2022); and greening is often measured based on the ESG environmental sub-indicators of enterprises or the number of green patents (Xu et al., 2021). However, these methods are insufficient in distinguishing between "strategic" and "substantive" green innovation. Based on a large number of empirical studies of A-share listed enterprises in China during 2009–2022, the overall digitization level of enterprises in China is currently on an upward trend. It is found that the positive impact of digital transformation on environmental performance is more significant for state-owned enterprises (SOEs) due to their adequate capital, stronger supervision and social responsibility awareness (Zhu et al., 2016). Empirical studies show that enterprise digital transformation significantly improves environmental performance and green patent output (Xie et al., 2023). However, under the information barrier and regulatory policy lag between government and enterprises, enterprises may adopt more strategic green innovations, especially under the financial incentives of green bonds, and non-state-owned enterprises are more inclined to such behaviors (Ji and Zhang, 2024). Digital transformation can positively affect environmental performance in both manufacturing and non-manufacturing industries. However, manufacturing industries are more vulnerable to both technological and financial constraints due to their larger actual inputs in the production chain, and are more likely to adopt strategic green innovations under green bond incentives; whereas in heavily polluting industries and non-heavily polluting industries, different heterogeneous characteristics are shown: heavily polluting industries are more likely to adopt substantive green innovations to improve environmental performance under strict regulation (Shi et al., 2023)

3. The innovations of this paper are mainly reflected in the following aspects:

(1) Innovations in theoretical construction: Based on the framework of "technology-economy paradigm", this paper for the first time systematically considers the digital transformation and greening development of enterprises as a mutually coupled process, and constructs a theoretical framework for the synergistic development of digitization and greening as well as their intrinsic mechanism of action, and distinguishes the inherent differences between substantive and strategic green innovation. It constructs a theoretical framework for the synergistic development of digitalization and greening and its intrinsic mechanism, and distinguishes the intrinsic differences between substantive and strategic green innovation. This framework helps to deepen the understanding of how digital transformation affects the green development of enterprises.

(2) Innovation of the coupling measurement method: based on the traditional measurement method, this paper proposes to adopt the multi-model fusion methods, such as PCA, TOPSIS and FEMA, to construct comprehensive indicators to dynamically and finely measure the coupling status of enterprise digitalisation and greening. This method can avoid the possible bias of relying solely on keyword statistics or ESG sub-indicators, provide more dimensional support for the quantification of the degree of coupling at the micro level of enterprises, and construct a multi-dimensional coupling measurement system to more accurately reflect the level of synergistic development of digitization and greening.

(3) Multi-level empirical analysis: this paper utilizes the period of 2009–2022 panel data of a large number of A-share listed companies, not only explores the coupling effect at the enterprise level, but also systematically analyzes the heterogeneity differences within industries and enterprises (one, two, three industries, manufacturing and non-manufacturing industries, and different types of manufacturing companies), to provide a more targeted empirical evidence basis for policy formulation.

4. The coupled and coordinated development status of digitalisation and greening in the agriculture industry. With the growth of the global population and the intensification of climate change, traditional agricultural production models face severe challenges. Digital agriculture and green agriculture, as two emerging paradigms, provide potential pathways for agricultural transformation. According to the study by Wang and Tang (2023), the overall trend of agricultural digitization and greening in various regions of China is moving toward coordinated development.

Existing literature has analyzed both digital and green agriculture. In terms of digital agriculture, the application of big data to agricultural production has effectively enhanced the responsiveness of agricultural technicians to farmers' technical needs (Kosior, 2017), significantly improving agricultural production efficiency and promoting rural revitalisation (Qu et al., 2018). Research by Dayıoğlu and Turker (2021) shows that many agricultural enterprises have launched digital transformations, strengthening their overall capabilities and core competitiveness. At the same time, digital agriculture has sparked reflections on the future of food production. Lioutas et al. (2021) indicate that technology can address food issues by simultaneously improving food yield and quality. The transition to digital agriculture may lead to systemic changes (MacPherson et al., 2025). Research by Luo et al. (2025) demonstrates that digital transformation promotes rural income growth, optimizes resource allocation, and enhances resilience. However, excessive digitization may widen income gaps and lead to the outflow of agricultural resources.

As agricultural resource and environmental issues become increasingly prominent, green development has become the mainstream of agricultural progress. The efficiency of green development in rural China has shown a fluctuating upward trend, promoting sustainable agricultural development. Green agriculture emphasizes improving agricultural production efficiency while protecting the ecological environment. Barbier (2025) analyzed the key structural characteristics of agricultural economies and their environmental impacts, assessing the importance of agriculture for food security. However, straw burning has led to soil degradation, negatively affecting food safety and sustainable agricultural development (Fang et al., 2020).

Overall, existing literature has explored the coupling of digital and green agriculture in terms of research scope, impact effects, and implementation pathways, and has examined the relationship between the two. This study aims to enrich the understanding of the specific pathways and mechanisms of coordinated development between digital and green agriculture.

2 Modeling approach

In the context of digital transformation and greening development, the effective integration of digitalisation and greening is crucial to the sustainable development of enterprises. In this paper, the degree of coupling coordination of enterprises in the process of digital transformation and greening development is measured by the principal component analysis (PCA) method, combining the entropy weight method, the TOPSIS model, and fuzzy analysis. In the following, the steps and formulas of PCA analysis will be introduced in detail, and their application in the degree of coupling and coordination of digital and green will be elucidated.

2.1 Number-green coupling model

2.1.1 Number-green coupling coordination degree

In the process of achieving high-quality economic development, digital transformation and green development, with their unique endowments of factors, have provided a constant internal driving force to optimize the industrial structure, promote iterative upgrading of productive forces, and build a modernized industrial system. From a micro perspective, digital transformation focuses on the use of digital technology and data-driven automation and intelligent development of enterprises, while greening development emphasizes environmental protection, resource conservation and sustainable development. Therefore, the coupling of digitalisation and greening can be defined as a comprehensive measure of the synergy between digital systems and greening systems and their interaction in the process of achieving digital transformation and green development of enterprises. This metric can reflect the ability of enterprises to utilize digital technology to enhance green practices and also show the potential of enterprises to achieve sustainable development through innovation drive. A higher degree of digital-green coupling coordination indicates that the enterprise has achieved a higher level of integration in the process of digital transformation and greening development, and can promote the simultaneous enhancement of economic and environmental benefits more efficiently; on the contrary, a lower degree of coupling coordination reflects the enterprise's inadequacy in the integration of digitalization and greening.

Drawing on the ideas of Huang and Gao (2023) and Jiang et al. (2023), this paper measures the degree of coordination of digital-green coupling at the micro-enterprise level based on the three-dimensional perspectives in the two systems of digital transformation and greening development, respectively. As shown in Figure 1, the three dimensions of the digital transformation system are the digital innovation dimension (measured by enterprise digital patent applications, dig1), the digital technology dimension (measured by digital intangible assets, dig2), and the digital investment dimension (measured by the percentage of investment in intelligent equipment, dig3); the three dimensions of the greening development system are the green innovation dimension (measured by greening patent applications, gre1), the green investment dimension (measured by green investment, gre1), and the green investment dimension (measured by green investment, gre1), (measured by the greening patent application, gre1), green performance dimension (measured by the green governance performance score of enterprises, gre2), and green cognition dimension (measured by the cognitive word frequency of green executives of enterprises, gre3); In the context of the interaction of the two systems of digital transformation and greening development, the article constructs the digital-green coupling coordination degree of micro-enterprises.

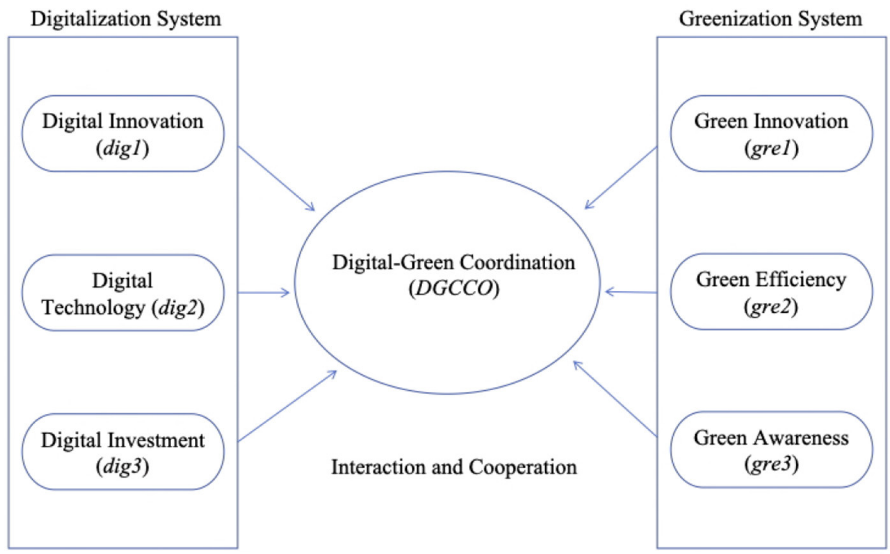

FIGURE 1
Schematic diagram of the structure of the measurement of the coordination degree of digital-green coupling.

2.2 PCA model

PCA is a dimensionality reduction technique used to transform multiple correlated variables into a new set of uncorrelated variables (principal components) through linear transformation. This method can help extract key features from data and reduce data redundancy. For multiple-dimensional indicators in digital and greening systems, PCA can effectively integrate key information from each dimension to reveal the relationship between digitalisation and greening systems.

2.2.1 Standardized processing

Since the indicators of each dimension (e.g., digital innovation, green performance, etc.) of the digital system and the greening system may have different scales, direct comparison of these variables will be affected by the scales, and therefore, standardization is needed. The purpose of standardization is to transform each variable into a standard normal distribution with the same mean (0) and standard deviation (1). The formula is:

$$z_i = \frac{X_i - \mu_i}{\sigma_i}$$

Where X_i is the original data, μ_i is the mean value of the variable, σ_i is the standard deviation of the variable, and z_i is the standardized data. Through standardization, the dimension indicators in the digital system (e.g., digital innovation, digital technology, digital investment) and the greening system (e.g., green innovation, green performance, green cognition) are changed to dimensionless data, which is convenient for subsequent analysis.

2.2.2 Principal component analysis (PCA)

The purpose PCA is to extract a new set of uncorrelated variables (principal components) by linearly transforming the standardized data. Each principal component is a linear combination of the original variables, and these principal components are ranked in descending order of the variance they can explain. The main steps of PCA are as follows: Calculation of covariance matrix: First, the covariance matrix is calculated for the standardized data, indicating the correlation between the variables. Calculating eigenvalues and eigenvectors: eigenvalues and eigenvectors are obtained by eigenvalue decomposition of the covariance matrix. The eigenvectors determine the direction of the new principal component, and the eigenvalues represent the variance explained by that principal component. Select Principal Components: Based on the magnitude of the eigenvalues, select the principal components that explain the most variance in the data. Generally, the first few principal components are chosen to reduce dimensionality while retaining the main information of the data. Through the above steps, scores for each observation on the principal components are obtained, and these scores indicate the position of the observation on each principal component of the digitization and greening system.

2.2.3 Calculating principal component score differences

After obtaining the principal component scores of each observation on the digitization system and the greening system, we need to calculate the difference between the scores of these two systems on the different principal components. The purpose of calculating the difference is to quantify the incongruence between the digitized and greened systems on each dimension. For the principal component, the score difference can be calculated by the following formula:

$$\text{diff}_i = \left(\text{PCA}_{(A_i)} - \text{PCA}_{(B_i)}\right)^2 \quad (i = 1, 2, 3)$$

Where PCA_{A_i} and PCA_{B_i} are the scores of the digitized system and the greened system on their principal component, respectively, and diff_i denotes the square of the difference between their scores on this principal component.

2.2.4 Calculating the degree of coupling coordination

The degree of coupling coordination is an important indicator of the degree of coordination between digitalisation and greening systems. The higher the degree of coupling coordination, the stronger the coordination between the two systems, and the more efficiently the enterprise can realize the win-win situation of economic and environmental benefits. The coupling coordination degree is calculated as:

$$\begin{aligned}\text{Coupling Degree} &= \sqrt{\sum_{i=1}^{3} \text{diff}_i} \\ &= \sqrt{(\text{PCA}_{A_1} - \text{PCA}_{B_1})^2 + (\text{PCA}_{A_2} - \text{PCA}_{B_2})^2 + (\text{PCA}_{A_3} - \text{PCA}_{B_3})^2}\end{aligned}$$

Where Coupling degree denotes the degree of coupling coordination between digitization and greening systems, and diff_1, diff_2 and diff_3 are the squared differences in the scores of each principal component, respectively. In this way, the calculated coupling coordination degree can comprehensively reflect the overall coordination between digitization and greening systems. If the coupling coordination degree is low, it indicates that the synergy between the digitization and greening systems is weak, and the enterprise may need to strengthen the integration and collaboration between the two.

2.2.5 Plot of differences in principal component scores

The Principal Component Score Difference graph shows the difference between the scores of the digitization system and the greening system on each principal component, revealing the similarities and differences between the two systems on each dimension.

Figure 2 demonstrates the results of the PCA analysis of the coupling between digital transformation and green development, presenting the differences in the scores in Principal Component 1 (PC1), Principal Component 2 (PC2), and Principal Component 3 (PC3), respectively. The score difference plots for each principal component indicate that the coupling between digital transformation and green development varies significantly across samples. Principal component 1 reflects the most important source of change in the data, with large differences in scores, especially as certain samples show significant peaks on this principal component, indicating that the coupling between digitalisation and green development is more prominent in these samples. While principal component 2 also demonstrates differences in scores across samples, the peaks appear in different locations, suggesting that this principal component captures another level of coupling change, while principal component 3 shows smaller differences in scores, suggesting that it has less influence in the overall coupling, and may represent minor coupling factors or localized

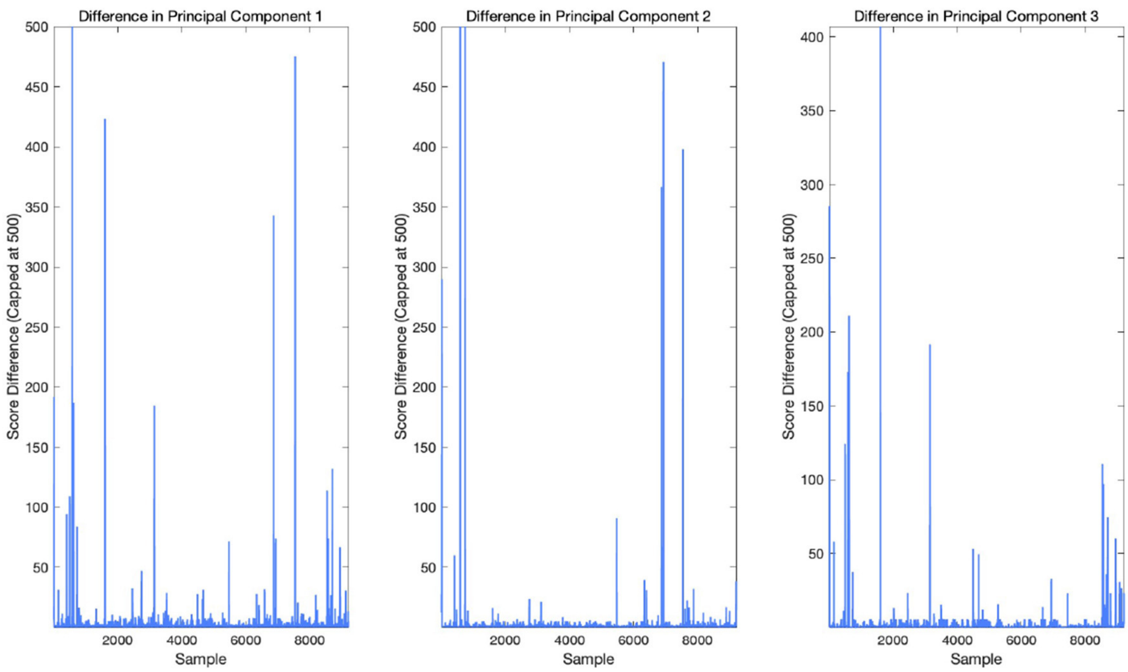

FIGURE 2
Difference between the scores of each principal component of the digitalisation system and greening.

sample changes. Overall, the principal component analysis helped to reveal the complex coupling mechanism between digitization and greening, and the spiky part of the score difference reflects the extreme performance of these variables in a particular sample, indicating that the coupling between digitization and greening is extremely strong or weak in certain industries or enterprises.

2.2.6 Trend of DGCO_PCA coupling harmonization degree from 2010 to 2022

Figure 3 illustrates the trend of the coupling coordination degree between the digitization system and the greening system over time. The overall trend shows that the value of the coupling coordination degree shows an upward trend, especially between 2016 and 2020, when the coupling coordination degree has increased significantly. This suggests that the coordination between digitization and greening increased significantly during this period, and the two systems may have interacted and promoted each other more in the process of synergistic development. After 2020, although the coupling coordination degree showed some fluctuations, it remained at a high level on the whole, which may imply that, although there may have been differences between digitization and greening systems in some years, they still maintained a relatively strong coordination. The trend of the coupling coordination degree reflects the interaction and impact of digitization and greening in business development. In particular, the growth in the period from 2016 to 2020 may be related to the fact that enterprises have strengthened their digital transformation while advancing their green development strategies during this period, thus achieving positive interaction and synergy between digitalization and greening. The emergence of fluctuations may be related to certain external factors or strategic adjustments made by enterprises in certain years, which may have affected the harmonized relationship between the two systems.

2.2.7 Heat map of digitalisation and greening system correlation

Based on the specific correlation coefficients in the heat map in Figure 4, this paper further provides a detailed analysis of the relationship between the dimensions of the digital system and the greening system. In the heat map, A1, A2, and A3 represent the three dimensions in the digitization system-digital innovation (dig1), digital technology (dig2), and digital investment (dig3), respectively; while B1, B2, and B3 represent the three dimensions in the greening system- -green innovation (gre1), green performance (gre2) and green perception (gre3). The specific correlation coefficients reveal the interaction between these dimensions and the strength of their mutual influence.

The heat map analysis in Figure 4 concludes that the relationship between the dimensions of the digitalisation system and the greening system is more complex, and the correlation is low. For example, the correlation between digital innovation and digital technology in the digitization system is only -0.0025, which is almost zero, indicating that there is no consistency in the changes of these two dimensions. Within the greening system, the correlation between green innovation and green performance is 0.0529, a weak positive correlation, while there is a slight negative

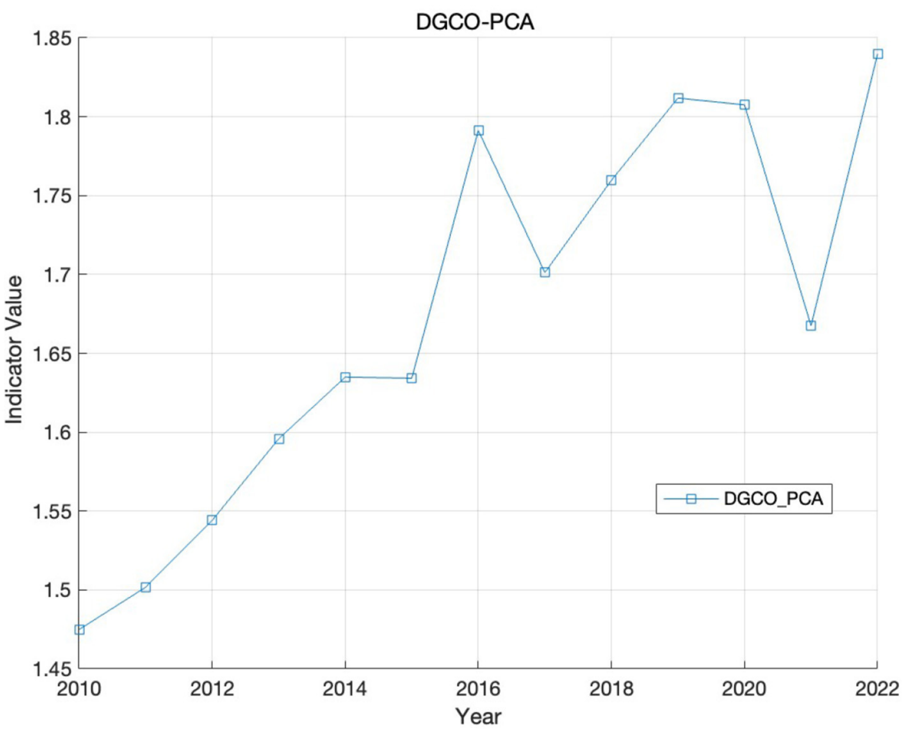

FIGURE 3
Trend of DGCO_PCA coupling harmonization from 2010 to 2022.

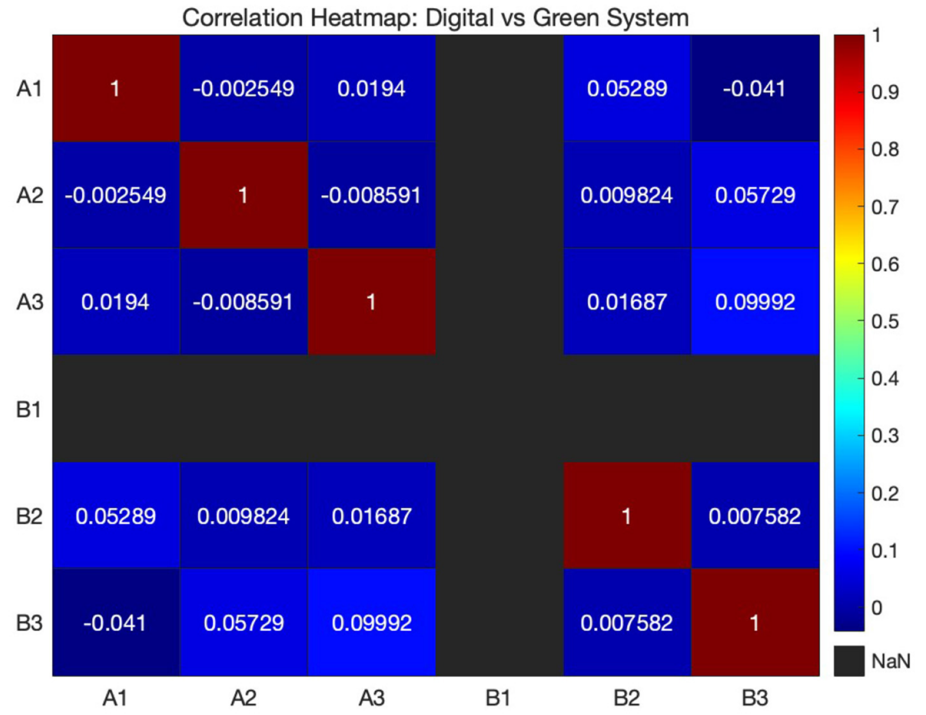

FIGURE 4
Heat map of digitalisation and greening system correlation.

correlation between green innovation and green perceptions (-0.041), suggesting that the link between them is weak. In the interaction between the digital system and the greening system, the correlation between digital innovation and green innovation is 0.0529, which shows some synergy, but overall, the interactions between the dimensions of the digital system and the greening system are not strong. For example, the correlation between digital innovation and green performance is 0.0098, which is almost zero, indicating that digital innovation has a limited impact on green performance, while the correlation between digital investment and green cognition is 0.0999, which indicates that digital investment has a certain facilitating effect on the improvement of green cognition.

Therefore, the coupling measurement of digitization and greening is crucial for the development of Chinese listed firms, which reveals the complex interaction between digital transformation and green development, identifies potential challenges and opportunities for firms in the process of dual transformation, and provides strong support for policy formulation.

2.3 Topsis and FEMA measurement method digital-green coupling indicator results

TOPSIS and FEMA each highlight a different analytical focus and value when examining the results of the coupled measurement of enterprise digitization and greening (as shown in Figure 5).

The TOPSIS method measures the overall coordination of the system by measuring the distance of each scenario from the ideal solution, and can visually reflect the relative performance of the two systems of digitization and greening in terms of the dimensions and their gaps from the ideal level (Zeydan and Çolpan, 2009). In contrast, the FEMA approach pays more attention to potential failure modes and their possible risks, and provides targeted improvement suggestions for the integration of digitization and greening through the investigation of potential failure links and causes within the system. Thus, while TOPSIS emphasizes the distribution of the ideal solution and the relative position of the actual sample to that ideal solution, FEMA focuses more on the identification and prevention of key risk factors (von Ahsen et al., 2022). Based on the above measurement methods, the TOPSIS results of this study show that the green coupling degree of the number of listed enterprises in China during the period from 2010 to 2022 shows a general trend of increasing year by year, especially since 2020, which shows that with the deep promotion of digital technology and the strengthening of green awareness, enterprises have achieved more significant results in the synergistic development of the two (He et al., 2023). This finding is consistent with the findings of PCA (Principal Component Analysis): PCA's downscaled synthesis of enterprises in the areas of digitalisation and greening shows that the close connection between the two systems is increasing, and the deep integration of the core elements is gradually appearing.

However, the results measured by FEMA are relatively flat and on the low side, suggesting that while the coupling of digitization and greening has made great strides, there are still vulnerabilities at the practical level that are susceptible to shocks in

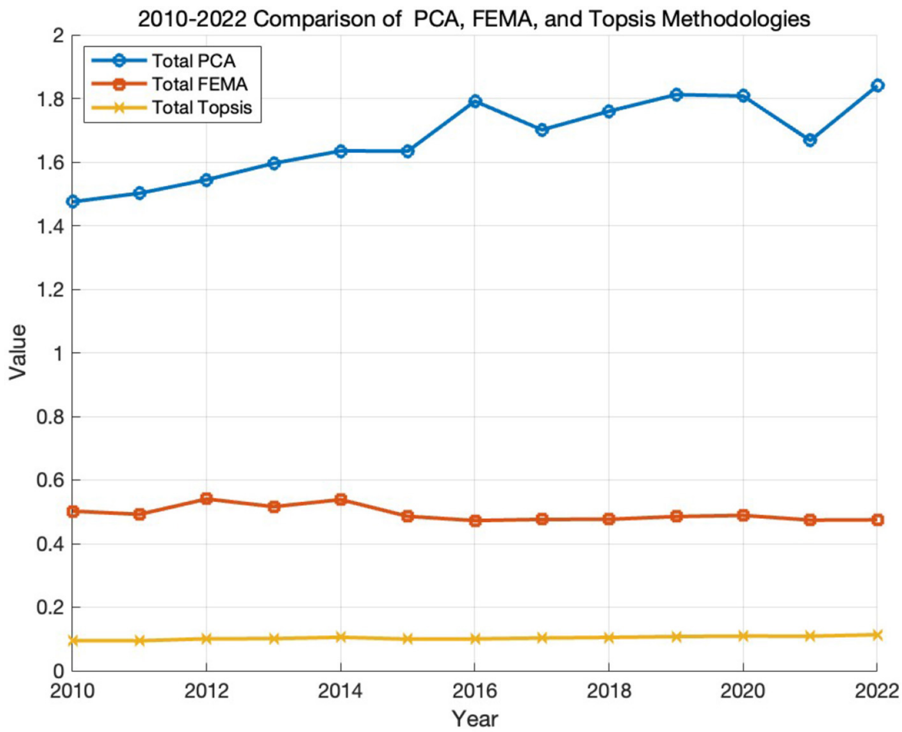

FIGURE 5
Comparison of DGCO_PCA, DGCO_TOPSIS, and DGCO_FEMA.

the policy and market environments. For example, in identifying key failure modes, FEMA points out that some enterprises may have incomplete implementation of green standards or lack of green regulation in the implementation of digitization technologies, and that these challenges may easily expose their digital-green integration to the risk of failure in the event of adjustments in the external environment or internal resources.

Compared to the smooth and low values of FEMA, the coupling values obtained by PCA are more optimistic and show a more significant climb after 2021. This finding is in line with the findings in the existing literature on digitally-enabled green innovation: the large-scale introduction of technologies such as big data, artificial intelligence and cloud computing by firms not only breaks through some of the resource and information constraints, but also better integrates eco-processes and eco-management practices, thus highlighting higher synergistic benefits (Lu et al., 2024; Ran et al., 2024; Bibri et al., 2024). This also indicates that the principal components summarized by PCA based on the overall correlation of data are more suitable for the deep integration of the 'Digital Green' system in the core areas.

In terms of the overall trend, the digitalisation-greening coupling and coordination degree of Chinese listed companies shows a steady increase from 2010 to 2022. The overall indicator was about 1.5 in 2010, rose to nearly 1.65 in 2015, and thereafter, although it fell back slightly in 2016, it once again jumped to a high of around 1.80, before falling back slightly to 1.72 in 2021 and returning to a new high of 1.85 in 2022. This overall rising trend is consistent with the rising trend of industrial digitization levels measured by the China Academy of Information and Communication Research (2022), which shows that the digitization of China's industries has risen from 26.09% in 2015 to 34.79% in 2020, with an average annual growth rate of 5.93%. This shows that under the dual path of "digitalisation-driven-green transformation", listed companies have formed an increasingly close synergistic relationship between informationization and ecological governance, demonstrating the superimposed effect of the national "Digital China" and "carbon neutral" strategies. As pointed out by Zhao S. et al. (2023), the relationship between environmental regulation and corporate green innovation in China has changed from a one-way constraint to a two-way interaction in the early stage, and the intervention of digital technology further promotes the deepening of this interaction. It is worth noting that the short-lived fall in overall coupling coordination in 2016 is related to the adaptive adjustments of enterprises at the beginning of the supply-side structural reform in that year. Wei et al. (2024) study shows that at the beginning of the supply-side reform, some enterprises reduced their digital inputs in response to the capacity compression, which led to the short-term disconnection between digitalisation and the greening process. The high oscillation after 2020, on the other hand, reflects the interactive process of accelerated enterprise digital transformation and deepened greening transformation in the context of the epidemic. Chen and Wang (2024) find that enterprise digital transformation indirectly promotes ESG performance by promoting enterprise structure optimisation, improving green innovation capacity, and reducing inefficient investment, which is in line with the The overall trend observation of this paper is consistent. Although there are differences in the degree of digital-green coupling between different measurement methods, the overall conclusion shows that Chinese listed companies have made positive progress in the synergistic process of digitalisation and greening, and still face risks and challenges in some aspects that cannot be ignored. The continuous upward trend of TOPSIS and the significant growth in PCA together reflect the overall potential of integration, which provides confidence for further deepening digital-green integration at the macro level. On the macro level, the rising trend of TOPSIS and the significant growth of PCA reflect the overall integration potential of enterprises, which provides confidence for further deepening digital green integration; while the risks and weaknesses revealed by FEMA warn enterprises that they need to focus on improving the details of system integration and the actual implementation progress. In the future, enterprises should take into account the advantages of different methodologies to ensure that the distance between the overall goal and the ideal solution continues to narrow, while accurately identifying and preventing key risk factors, to achieve sustainable and high-quality digital and green transformation.

2.4 Data description

The firms' data selected for this paper come from the Cathay Pacific (CSMAR) database, and after deleting the samples of firms whose total assets are less than total liabilities and whose years of establishment are less than one, 9,197 observations of A-share listed firms are obtained for the period from 2010 to 2022.

3 Analysis of the measurement results of the coupling coordination degree of digitization and greening of listed companies in China

3.1 Degree of number-green coupling: comparison and analysis of industry number-green coupling indicators and overall number-green coupling indicators

3.1.1 Characterization of the coordination degree of digitization-greening coupling of first industries under the PCA measurement approach

Figure 6 shows the first industry (agriculture, forestry, animal husbandry and fisheries) DGCO_PCA development trend. It starts from the lowest point, at about 1.1 in 2010, and slowly climbs to about 1.3 in 2011–2013; it reaches a peak of about 1.35 in 2014 and then continues to go downward in 2015–2017, dropping to 1.1 in 2017 around; then bottoming out from 2018 and climbing to around 1.45 in 2022; the second industry (manufacturing, construction, etc.) has the highest level of overall coupling coordination, at around 1.4 in 2010, then climbing steadily to around 1.7 in 2012–2014, and then stabilizing briefly after 2015; and breaking through again in 2016 to a 1.9 of the high

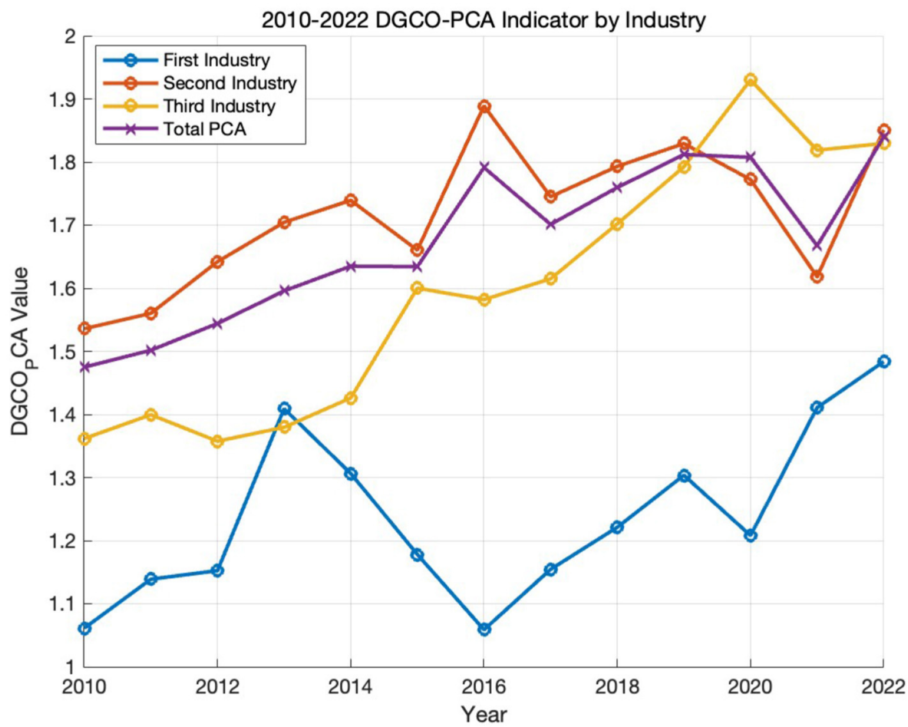

FIGURE 6
DGCO_PCA industry digital-green coupling indicator vs. overall digital-green coupling indicator.

level, a slight retracement to around 1.8 in 2017, and an overall high fluctuation between 1.8 and 1.85 in 2018–2020, a slight drop to 1.75 in 2021, and then a rapid rebound to a peak above 1.85 in 2022; the coupling coordination degree of the third industry (services) has been at the highest level since 2010 started at 1.3, climbed steadily to 1.55 in 2011–2013; stagnated slightly in 2014–2015, around 1.6; grew rapidly again after 2016, reaching a high of more than 1.9 in 2019; fell slightly to 1.85 in 2020, fell in 2021 down to 1.7 in 2021, and back up again to 1.85 in 2022.

Comparing the degree of coordination of the digitization-greening coupling between the three major industries and the aggregate, significant divergent features can be found:

First, the first industry has the lowest overall level and the largest fluctuation, and its gap with the overall level is the most obvious. This phenomenon is closely related to the basic conditions of industrial digitization. According to data from the China Academy of Information and Communication Research (2022), the digitization level of the service sector is about 35%, the industry is about 20%, while agriculture is only about 9%. This suggests that the agricultural segment is still lagging at the digitization infrastructure level, which in turn affects its synergies with greening. Shi et al. (2022) further explains this phenomenon, pointing out that agribusinesses' relatively decentralized organizational structure and weak capital strength limit their ability to invest in digitization and ESG, which leads to a coupled coordinated the coupling coordination of the second industry that is lower and more volatile.

To further investigate the digital-green coupling pathways in the agriculture and food industry, we conducted the following mechanism analysis.

1. Mechanisms promoting digital-green coupling in agriculture. Enhancing the coupling degree between digitalisation and greening in agriculture is recognized as a crucial pathway for achieving sustainable agricultural development in China. Theoretically, agricultural digitalisation facilitates green transformation through three primary mechanisms: precision empowerment via information, efficient resource allocation, and scientific optimisation of decision-making.

Firstly, digital technologies enable real-time monitoring and precise intervention throughout agricultural production, overcoming traditional information asymmetries. For example, Wang et al. (2023) showed that the application of IoT in agricultural water management improved water-use efficiency and significantly reduced diffuse source pollution risks. Secondly, digitalisation reconstructs resource allocation by enabling precision input of agricultural resources. The big data-based precision fertilization technology can reduce fertilizer usage while maintaining or even increasing crop yields (Song et al., 2022). Further, agricultural data analytics systems can optimize production decisions and help farmers adjust practices to environmental limits, thereby achieving more eco-friendly production modes (Yang and Solangi, 2024).

It is important to note the stage-dependent nature of digital-green coupling in agriculture. Wang and Tang (2023) demonstrated that, in early stages of digitalisation, coupling remains limited; however, synergy accelerates as digital technology penetrates more deeply. This aligns with the 2024 Central Document No.1, which emphasizes deepening rural reforms, guiding farmers toward entrepreneurial activities suited to family operations, and developing courtyard and under-forest economies. These emerging agricultural systems provide practical platforms for advancing digital-green coupling.

2. Mechanisms promoting digital-green coupling in the food industry. The coupling mechanisms of digitalisation and greening in the food industry both share similarities and exhibit industry-specific distinctions compared to agriculture. In particular, coupling is strengthened primarily through: full-chain supply chain visualization, intelligent optimisation of production processes, and green consumption guidance.

In recent years, growing concerns over food safety and sustainability have accelerated digital transformation in the food sector. The application of blockchain technology in the food supply chain can significantly reduce food waste rates and decrease carbon emissions, owing chiefly to enhanced transparency, improved inventory turnover, and optimized logistics (Omar et al., 2024; Shakhbulatov et al., 2019). The use of big data and Internet of Things (IoT) across the food supply chain, as also highlighted in your knowledge base, is driving intelligent, precise, and real-time environmental governance and supply chain optimisation.

Intelligent process optimisation is another critical mechanism. Xiang et al. (2021) and Waltersmann et al. (2021) revealed that companies applying artificial intelligence to optimize production processes achieved significant improvements in average energy efficiency and water resource utilization efficiency. This evidence connects with your knowledge base conclusion that higher proportions and efficiency in fiscal environmental governance at the local government level are linked to better environmental outcomes, underlining the central role of efficient resource allocation for greening.

In addition, digitalisation reshapes consumer behavior, indirectly driving greening in the food industry. As shown by Palmieri et al. (2024), consumers were guided toward eco-friendly products when food companies disclosed environmental impact information online, exerting pressure on companies to adopt greener production methods. This supports the policy orientation in your knowledge base: "advancing food conservation across the supply chain, promoting a culture of thrift, and reducing food loss and waste".

3. Synergy and constraints in digital-green coupling. While digitalisation can significantly advance greening, its synergy is not always positive. Jiang et al. (2023), through empirical research on Chinese-listed agricultural and food firms, found heterogeneity in coupling effects depending on ownership structure. State-owned enterprises, subject to stricter government oversight and better regulatory information flows, saw more pronounced improvements in environmental performance post digitalisation, consistent with the conclusion from your knowledge base: "the positive effect is more significant in state-owned enterprises compared to non-state enterprises".

Capital constraints represent another important factor influencing digital-green coupling. Deichmann et al. (2016) identified that substantial upfront investment is required for digital transformation in agriculture and food industries; however, environmental benefits may lag, resulting in potential "digital-green decoupling" in the short term. This challenge is particularly

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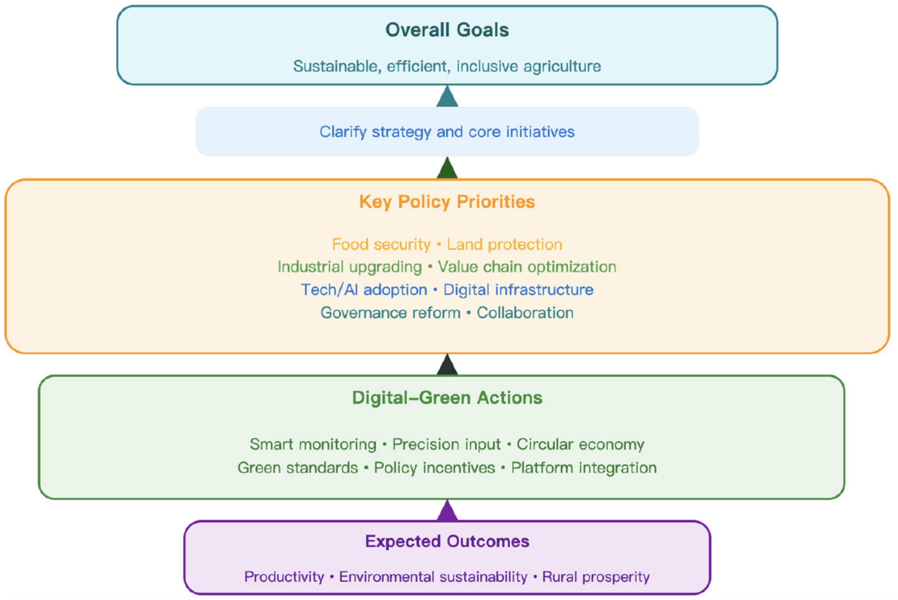

FIGURE 7
Diagram of the digital-green coupling mechanism in the agriculture and food industry.

acute among small and medium-sized enterprises and constitutes a key hurdle for further enhancing coupling in these sectors.

In summary, the digital-green coupling in China's agriculture and food sectors is a systemic and complex process; the root mechanism could be concluded in Figure 7, requiring a coordinated approach that integrates technology adoption, institutional innovation, and market mechanisms. As highlighted in the 2024 Central No.1 Document and corroborated by your knowledge base, stronger promotion of digital solutions in rural revitalisation and food system transformation is essential to achieving high-quality and green development in these key industries.

3.1.2 Characterization of the coordination degree of digitization-greening coupling of second and third industries under the PCA measurement approach

The second industry has the highest and relatively stable coupling degree, indicating that the manufacturing and construction industries have achieved significant results in the "dual transformation". This is consistent with the findings of Chen and Hao (2022) on digital transformation and enterprise performance, that is, the digital transformation of manufacturing enterprises not only improves economic performance, but also brings about significant improvement in environmental performance, and the study of Shao and Chen (2022) also shows that the government's support for R&D in the manufacturing industry promotes the enterprises' development in the field of green technology. Promotes enterprises' innovation in the field of green technology, which further strengthens the synergistic development of digitization and greening in the second industry.

The performance of the third industry is in the middle of the list, with a relatively fast rising speed but high volatility, reflecting the flexibility of the service industry in the application of digital technology and the structural challenges in the greening process. Lin and Teng (2024) study on the digitization of the service industry and its environmental performance shows that, although the increased digitization of the service industry can significantly reduce energy consumption and carbon emissions, this effect is subject to the influence of service providers' digitalisation and environmental performance. Emissions, but this effect is affected by the structural heterogeneity within the service industry, which leads to greater volatility in its coupling coordination. The overall curve lies between the second and third industries, driven by the manufacturing industry and characterized by fluctuations in the service industry. This trend reflects the transformation of China's economic structure, in which the stable support of the second industry and the rapid growth of the third industry together shape the overall digitalisation-greening synergy. The change in the degree of digitalization of China's overall industry is mainly driven by digital transformation factors, which contribute up to 168.34% during 2016-2020, of which 23.03% is contributed by the manufacturing industry, 8.14% by the financial industry, and 14.13% by the construction industry, which is basically in line with the trend of the evolution of the degree of coordination of the industrial coupling observed in this paper.

3.1.3 Comparative analysis of the results of the multivariate methodology

In terms of overall trends, all three methods show a gradual increase in the coupling of digitization and greening among listed companies, indicating that the synergistic effect of the 'dual transformation' is growing among Chinese companies.

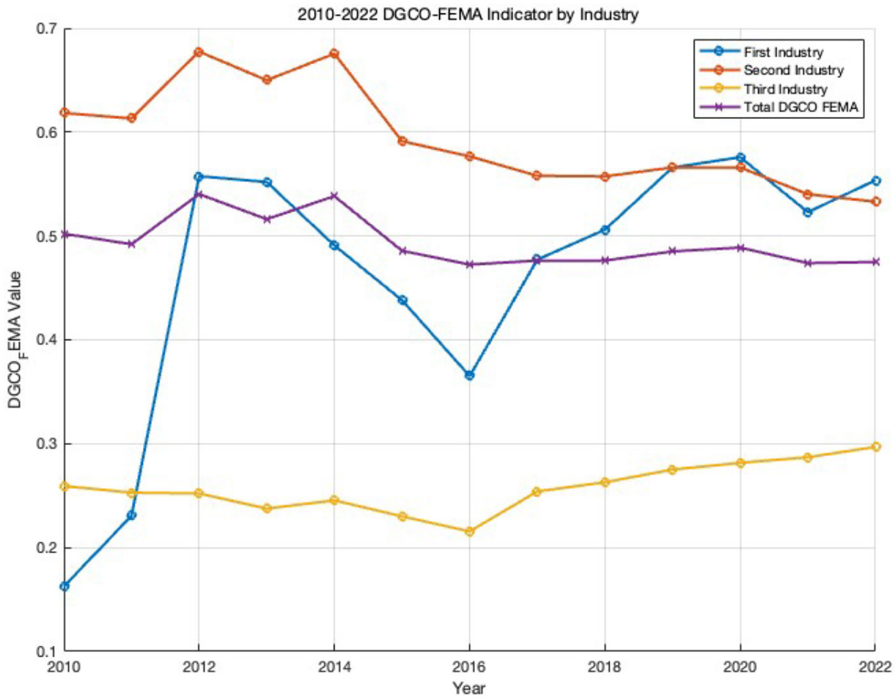

FIGURE 8
DGCO_FEMA industry digital-green coupling metrics vs. overall digital-green coupling metrics.

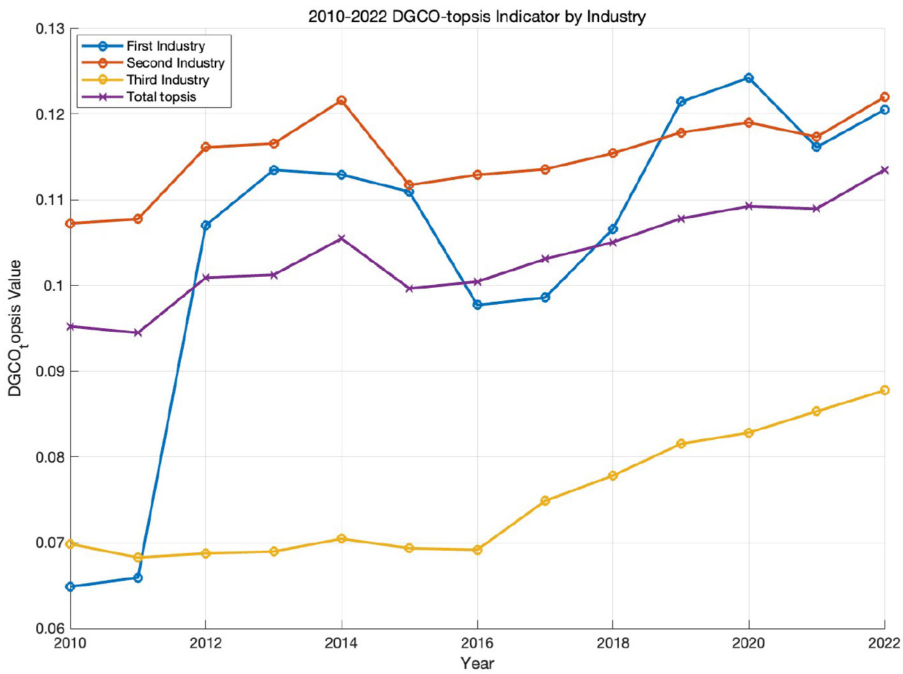

FIGURE 9
DGCO_TOPSIS industry digital-green coupling metrics vs. overall digital-green coupling metrics.

The PCA method shows the most obvious growth trend, especially after 2020, while the FEMA method shows a relatively flat growth, highlighting the risks and challenges of system integration (as shown in Figure 8); the TOPSIS method shows an accelerated growth after 2016, reflecting the process of enterprises approaching the ideal state (as shown in Figure 9); secondly, in terms of industry differences, all three methods reflect that the second industry is approaching the ideal state. Method, on the other hand, shows accelerated growth after 2016, reflecting the process of enterprises approaching the ideal state; second, in terms of industry differences, all three methods reflect that the second industry is leading the way in coupling digitization and greening, while the first industry has the most fluctuating progress, and the third industry lags in comparison. This conclusion is highly consistent with the findings of existing studies. Yin et al. (2022) point out that the manufacturing industry has the most significant synergies between digital technology application and green innovation; Mondejar et al. (2021) study shows that the digitalization of agriculture and greening integration has progressed but faces constraints such as insufficient infrastructure; and Lin and Teng (2024) highlights the limiting effect of internal structural heterogeneity in the service industry on the synergy between its digitization and greening; thirdly, in terms of methodological characteristics, the PCA method integrates the data by downscaling to show the overall synergy more comprehensively; and the FEMA method focuses on the system risk and failure points, revealing potential challenges in the coupling process; and the TOPSIS method reflects the performance of each industry in the optimal state through the distance from the ideal solution. The synergy between digitization and greening requires not only focusing on the overall trend, but also analyzing the system risk and optimal practice, which is in line with the original intention of this paper's multi-method measurement.

3.2 Digital-green coupling degree

3.2.1 Differences in manufacturing and industry-wide coupling under PCA measures

From the trend of the number-green coupling degree calculated by the principal component analysis (PCA) method (as shown in Figure 10), the coupling degree of the manufacturing industry shows an increasing trend year by year during the period from 2010 to 2022, especially after 2015, the number-green coupling degree of the manufacturing industry increases significantly. Specifically, the time series of the coupling degree of the manufacturing industry shows three distinct stages of development: the first stage (2010–2014): a period of steady growth. In this phase, the manufacturing digital-green coupling degree increased from about 1.4 in 2010 to about 1.7 in 2014, with an average annual growth rate of about 5.0%. During this period, the digital transformation of China's manufacturing industry is still in its infancy, mainly manifesting itself in the construction of information technology infrastructure and the digitization of production processes, while the concept of green development has begun to be introduced into the transformation strategy of the manufacturing industry. Chen et al. (2025) study shows that the digitalization and greening in this stage have not yet formed a systematic synergy, and they are mainly independently developed, with limited mutual promotion; the second stage (2015–2019): a period of rapid enhancement. During this period, the coupling degree of digitalisation and greening in the manufacturing industry has risen rapidly from 1.7 to a high level of more than 1.85, and the average annual growth rate has increased to about 3.5%. This period corresponds to the comprehensive promotion of China's "Internet+" strategy, "Made in China 2025", and the construction of eco-culture, and the synergistic effect of the policies is significantly enhanced. The digitalisation and greening strategies of manufacturing enterprises in this phase began to shift from parallel development to synergy, and the application of digital technology in the greening of the production process increased significantly. In particular, the high point in 2016 (about 1.9) is highly coincident with the introduction of the Industrial Green Development Plan (2016–2020), indicating that policy promotion is a key factor in the acceleration of digital-green coupling in this stage; Stage 3 (2020–2022): fluctuating adjustment period. During this period, the manufacturing industry's number of green couplings shows high fluctuation characteristics, from about 1.85 in 2020, fell slightly to 1.75 in 2021, and then rebounded to more than 1.85 in 2022. This fluctuation is closely related to the reconstruction of the global supply chain under the impact of the epidemic, the fluctuation of raw material prices, and the strategic adjustment of the manufacturing industry under the goal of "double carbon". Liu et al. (2023) showed that Chinese manufacturing enterprises faced survival pressure during the epidemic, and the synergy between digitization and greening inputs was weakened in the short term, but with the policy adjustments and economic recovery of the epidemic in 2022, the manufacturing industry's growth was expected to increase. With policy adjustments and economic recovery, the degree of digitization and greening development in the manufacturing industry rebounded rapidly.

In contrast, the industry-wide digital-green coupling degree, although also rising year by year, is growing at a relatively slower rate and with greater volatility. The PCA methodology shows that from 2010 to 2022, the industry-wide digital-green coupling degree rose from 1.5 to 1.85, with an overall increase of 23.3%, which is lower than that of the manufacturing industry, which increased by 32.1% over the same period. This difference suggests that the overall industry's digitization and greening integration process is affected by the uneven development between different industries.

3.2.2 Comparative analysis of the results of the multivariate methods

The results derived from all three measurement methods in Figure 10 show that the digital-green coupling of the manufacturing industry as a whole is higher than the level of the whole industry and grows faster, with an average annual growth rate of 2.3% (PCA), 1.8% (FEMA), and 2.5% (TOPSIS), respectively, while the corresponding growth rate of the whole industry is 1.7%, 1.2%, and 1.5%. This trend suggests that the manufacturing industry is indeed ahead of other industries in the synergistic advancement of digitization and greening, and is a forerunner in digital-green coupling.

In terms of fluctuation characteristics, the three methods differ in capturing the fluctuation characteristics. The PCA method shows that the manufacturing coupling reached a stage high (1.9) in 2016, followed by a slight pullback and then rise; the FEMA method shows that the manufacturing coupling fluctuated a lot in 2010–2015, and then tended to rise steadily after 2016; The TOPSIS method, on the other hand, captures an accelerating trend in manufacturing coupling after 2016. These differences may stem

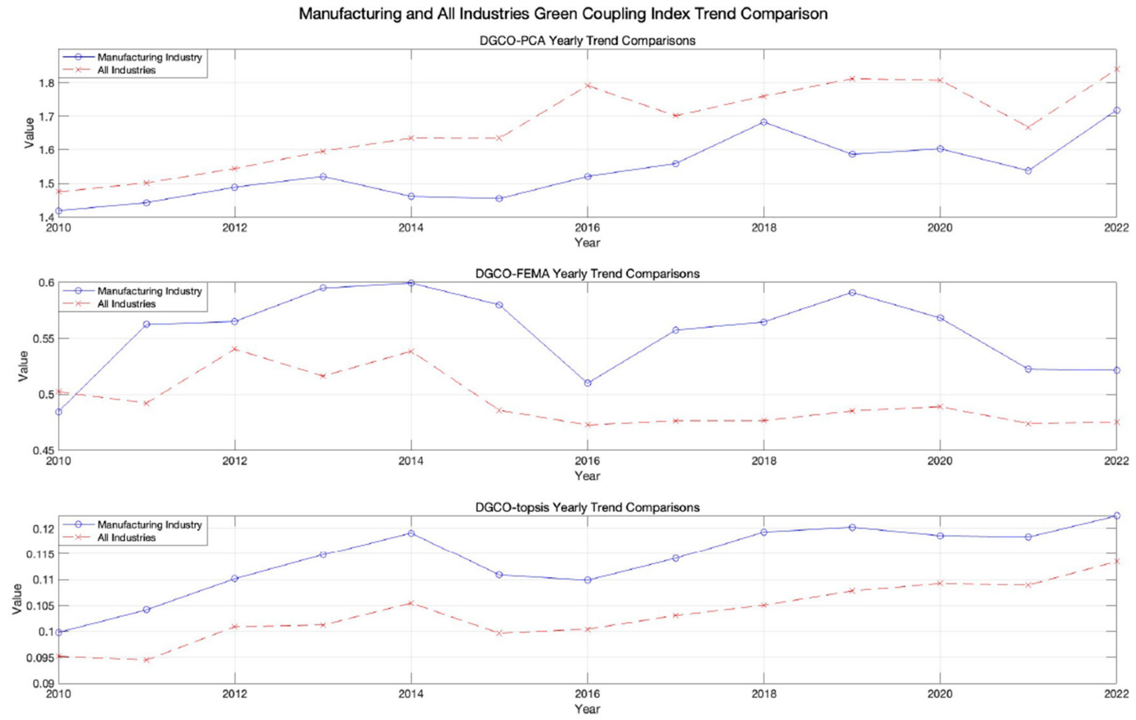

FIGURE 10
Manufacturing vs. industry-wide comparative analysis.

from the differences in data sensitivity of the three methods. In addition, the three methods also diverge in measuring the gap between the manufacturing and the industry-wide number of green couplings. The PCA method shows that the gap between the manufacturing and the industry-wide coupling is relatively stable until 2015, and then significantly widens after 2016; the FEMA method shows that the gap gradually narrows throughout the sample period; and the TOPSIS method shows that the gap widens instead after 2016. This measurement difference may stem from differences in data sensitivity among the three methods.

Despite methodological differences, there is a high degree of consistency among the three methods in identifying key turning points. Both the PCA and TOPSIS methods identify 2016 as an important watershed, while the FEMA method places more emphasis on the 2015–2016 shift. This high degree of consistency suggests that 2015–2016 is indeed a key turning point in the development of digital-green coupling in China's manufacturing sector. In addition, the three approaches provide complementary explanations for the abnormal fluctuations in the number-green coupling in 2020–2022. The PCA approach emphasizes the impact of systemic shocks; the FEMA approach highlights the role of risk accumulation; and the TOPSIS approach points out the deviation from the ideal state. Together, these three perspectives suggest that epidemic shocks lead to short-term fluctuations in the number-green coupling of manufacturing industries, but after the fluctuations have passed, they return to an upward path, indicating that a long-term trend in the number-green coupling has taken shape.

3.3 Number-green coupling degree: comparative analysis of number-green coupling indexes of listed manufacturing companies classified C09-C31 and overall number-green coupling indexes

This paper further penetrates inside the manufacturing industry and systematically analyses the degree of digitization-greening coupling coordination (DGCO_PCA) of different manufacturing industry segments based on the database of Chinese listed companies and the industry classification standard of China Securities Regulatory Commission (C09-C31). By comparing with the overall coupling coordination degree, it reveals the heterogeneous characteristics and evolution law of the development of digital-green coupling in each industry within the manufacturing industry.

3.3.1 General trends in segment coupling under the PCA measurement approach

From an overall perspective, the number-green coupling of manufacturing industry segments shows different growth trajectories between 2010 and 2022, with both commonalities and obvious differences. From the commonality point of view, the digital-green coupling indicators of most manufacturing subsectors show an overall upward trend, especially after 2015, where the growth accelerated, which is closely related to the "Made in China

2025" strategy and the in-depth promotion of the construction of the green manufacturing system. Liu et al. (2022) pointed out that the contribution of the digital economy to China's economic growth has increased significantly after 2015, while the digitalisation transformation of traditional manufacturing industries has accelerated, which has contributed to a significant increase in the digital-green coupling. At the same time, the digital transformation of the traditional manufacturing industry has accelerated, creating favorable conditions for the accelerated improvement of the digital-green coupling. 26 quickly caught up with the overall level after 2016, while sectors C15, C17, and C18 were consistently below the overall level.

3.3.2 In-depth analysis of a typical industry

To gain a deeper understanding of the heterogeneity of number-green coupling within the manufacturing industry, three representative types of industries are selected for detailed analysis in this paper (Comparison of green-coupled indexes of the C09-C31 counts of the classification of listed manufacturing companies and green-coupled indexes of the total PCA counts are attached in the Appendix Figures 11–14):

Type I: fast-growing industry (C09 food manufacturing industry, for example): the green coupling degree of the C09 industry has rapidly increased from about 1.3 in 2010 to nearly 2.0 in 2022, with an average annual growth rate as high as 3.5%, which is significantly higher than the overall level of the manufacturing industry. The coupling curve shows a clear "S"-shaped growth path: 2010–2014 is a slow growth period, 2015–2019 is a rapid increase period, and 2020–2022 is a stable and high period. Consumer preference constraints and food safety regulation, their digital transformation not only enhances economic performance, but also brings significant environmental performance improvement. Especially in the traceability of food production, the application of digital technology not only meets the regulatory requirements but also optimizes the efficiency of resource utilization and achieves a synergistic enhancement of digitalisation and greening. In addition, national policy support for food safety and green food is one of the driving factors. The revision of the Food Safety Law in 2014 and the promulgation of the "Healthy China 2030" Planning Outline in 2016 have provided policy drivers for the greening of the industry. Data show that the average annual growth rate of green patent applications in the C09 industry after 2016 exceeded 25%, and the synergistic effect of the "dual transformation" of digitization and greening has been significantly enhanced.

Type II: Fluctuating and developing industries (C15 leather, fur, feather and their products and footwear industry as an example): the digital-green coupling of the C15 industry shows a clear fluctuation, with a figure of about 1.2 in 2010, rising only to about 1.5 in 2022, and showing a clear decline over the period 2018–2020. This volatility reflects the challenges faced by the industry in the process of integrating digitization and greening. Zhang et al. (2024), in their study of government R&D subsidies and corporate innovation, point out that labor-intensive traditional manufacturing industries have obvious barriers to technological innovation and upgrading due to their relatively weak technological absorptive capacity and financial strength, leading to a relative lag in their digital transformation. At the same time, the C15 industry, as a typical representative of the traditional manufacturing industry, faces greater environmental pressure. The production process of this industry involves a large number of chemical treatments and wastewater discharge, and green transformation is costly and difficult. Data show that although the proportion of environmental protection investment in the industry as a percentage of operating revenue has increased from 1.2% in 2010 to 2.8% in 2022, it is still significantly lower than the 4.5% in the food manufacturing industry, which explains to a certain extent the slowness and volatility of the increase in its digital-green coupling.

Type III: Catching-up industry (C26 chemical materials and chemical products manufacturing industry as an example): The evolution of digital-green coupling degree in C26 industry shows obvious "catching-up" characteristics: it was at a relatively low level (about 1.3–1.4) in 2010–2015, and then rapidly increased after 2016, reaching a high level of more than 1.9 in 2022, which is almost equal to the overall level of the manufacturing industry. This evolutionary path suggests that, as a traditionally high-polluting and high-emission industry, the C26 industry has accelerated the convergence of digitization and greening in response to environmental pressures and policy guidance. Akhtar et al. (2024), in their study of the relationship between digital transformation and green innovation in the manufacturing sector, found that it is precisely in the industries with the most stringent environmental regulations that digital technologies contribute most significantly to green innovation. Particularly in the chemical industry, digital technologies significantly improve the environmental performance of companies by optimizing production processes, increasing resource efficiency and promoting green innovation. This "forcing mechanism" explains the rapid increase in the C26 industry's digital green coupling after 2016. 2016 was a key year for China's environmental policy to turn stricter, and the implementation of the 13th Five-Year Plan for Ecological and Environmental Protection put forward higher green development requirements for the chemical industry. During the same period, the rapid development of the industrial internet provided technical support for the digital transformation of chemical enterprises. This combination of policy pressure and technical support has contributed to the rapid increase in the digital-green coupling of the C26 industry.

4 Conclusion

By measuring and analyzing the coupling degree of digital transformation and greening development of Chinese listed companies, this paper draws the following conclusions:

The overall trend of the degree of digital-green coupling is positive. The measurement results based on the three methods of PCA, TOPSIS and FEMA show that although there are some differences in the values of the degree of digital-green coupling obtained by different methods, the overall trend shows that the synergistic development of digitization and greening has shown a year-on-year increase between 2010 and 2022. In particular, the coupling degree of digitization and greening has increased significantly between 2016 and 2020, indicating that while enterprises are promoting digital transformation, greening development has also been promoted simultaneously.

The degree of number-green coupling is significant in industry and firm heterogeneity. Differences in the degree of number-green coupling are more significant across subsectors and firm types. Specifically, some environmental and energy-intensive industries (e.g., C09 and C10) show more rapid coupling growth due to their stronger policy support and technological innovation. Resource-intensive industries (e.g., C15 and C18), on the other hand, face greater challenges, especially in terms of difficulties in technological upgrading and capital investment, leading to a relatively slow greening process. In addition, state-owned enterprises (SOEs) show a more significant positive impact in the integration process of digitalisation and greening transformation due to their stronger policy adaptability and financial support.

The synergistic effect of digitalisation and greening needs to be improved. Empirical analysis shows that digital transformation can effectively promote enterprise green innovation, improve resource utilization efficiency and reduce environmental pollution. Especially in intelligent manufacturing and green technology applications, the synergistic effect between digital technology and greening has been strong. However, despite the more significant role of digital transformation in promoting greening, there are still obstacles and challenges in the implementation process in certain industries, especially heavily polluting industries, especially policy lags and financial bottlenecks that may limit the actual effect of green innovation.FEMA measurements show that although the overall digital-green coupling is on an upward trend, in some years, especially after 2020, the volatility increases, revealing the risks that companies may face when implementing digital and green transformations. Specifically, companies may have an incomplete or inconsistent implementation of green standards and technology applications, and these issues may affect the synergy between the two. Therefore, further strengthening the policy guidance to optimize the path of digitalization and greening integration for enterprises is a key direction for the future.

Based on the results of the study, this paper suggests that policymakers should further strengthen incentives policies for green innovation, especially for industries with lagging technological updating, and should increase financial and technical support.

For the agricultural sector, policy interventions must be meticulously designed to accelerate the digital-green transition, building upon this study's findings of its current lag and volatility. First, enhancing digital infrastructure and promoting the adoption of smart agriculture are paramount. This includes targeted financial support, such as dedicated subsidies, tax incentives, and low-interest loans, as reflected in policies promoting digital and green R&D, to enable agricultural enterprises to integrate digital technologies such as IoT, big data analytics, AI, and precision agriculture tools. This strategic alignment with the "2024 and 2025 Central No. 1 Documents" underscores the importance of a digital-first approach. Second, precision monitoring and management through digital platforms should beprioritisedd for soil health, water usage, pest control, and weather patterns. This facilitates precise input application, reducing waste and environmental pollution, and contributing to the development of an "intelligent and refined pollution prevention and control system," as outlined in national policy directives. Third, strengthening green technology R&D and its practical application is critical. Public R&D funding should be directed toward low-carbon farming techniques, organic fertilizers, and water-saving irrigation, complemented by skill development programs that empower farmers to utilize digital tools for sustainable practices. Lastly, optimizing land use and resource management through continuous investment in the construction "of high-standard farmland", ntegrated with digital monitoring systems, is essential. This should be accompanied by water conservation technologies, agricultural waste valorisation, and robust rural environmental sanitation measures, including waste and sewage treatment.

For the food industry, which has demonstrated faster growth in segments such as C09 Food Manufacturing, future policies should emphasize enhancing supply chain transparency, production efficiency, and sustainable consumption. First, promoting digitalised green supply chains is crucial. This involves encouraging food enterprises to integrate ESG criteria into their supply chain management and supporting the adoption of blockchain and IoT for improved farm-to-fork traceability, thereby enhancing food safety and minimizing waste. Second, supporting green and smart manufacturing in food processing is vital. Financial assistance should be directed toward technology upgrades, such as energy-efficient machinery, AI, and big data for process contro,—and the adoption of circular economy models, including by-producvalorisationon and minimization of packaging waste. Third, fostering sustainable consumption patterns can be achieved by incentivising food companies to leverage digital platforms for disclosing product environmental impact information and supporting digital solutions for optimized inventory management to reduce food loss. These measures align with the broader strategic aims of the "2024 & 2025 Central No. 1 Documents".

At the same time, enterprises should focus on integrating green concepts into the digital transformation process, promoting the innovative application of green technologies, and enhancing the deep integration of digitalisation and greening. Future research can further explore the heterogeneous differences at the industry level and combine the global green development trend to provide theoretical support for enterprises to formulate more accurate green transformation strategies. The coupling measurement of digitization and greening proposed in this paper not only provides new research ideas for academics but also provides a practical decision-making basis for enterprises and policymakers. Deepening the synergy between digitization and greening, it provides new practical experience and theoretical basis for Chinese listed companies in the process of achieving high-quality and sustainable transformation. Looking ahead, as the digital economy and green development strategy continue to deepen, the positive interaction between the two is expected to play a more significant role in promoting the green and low-carbon transformation of enterprises and enhancing international competitiveness.

Data availability statement

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

Author contributions

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

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Supplementary material

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