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Under the context of smart agriculture: assessment of agricultural product distribution efficiency in various regions of China

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The efficient development of the agricultural product circulation industry, as a crucial component of agricultural growth, directly impacts the successful realization of the country's rural revitalization strategy. Despite the favorable trend in the development of China's agricultural product circulation industry, with continuous growth in the volume of agricultural product circulation and overall logistics turnover, challenges persist. There remains a prevalent emphasis on "heavy production and light circulation" in agricultural development, leading to high circulation costs and notably low efficiency. This situation necessitates imminent reforms within the agricultural product circulation industry. In response to emerging contradictions in the contemporary agricultural product circulation domain, the country has strategically advocated for digital development. The advancement of next-generation information technology has propelled the reforms within the agricultural product circulation industry and the exploration of intelligent technology applications in this field aligns with practical developmental needs. Firstly, this article constructs an evaluation framework for agricultural product circulation efficiency based on the perspective of dual online and offline circulation channels. Utilizing the data envelopment analysis (DEA) method, the study calculates the static efficiency of agricultural product circulation in China. Through regional comparisons, it is revealed that the overall efficiency of agricultural product circulation is highest in the eastern region, followed by the central and northeastern regions, with the western region lagging behind. Secondly, employing the Malmquist index model, the study investigates the changes in total factor productivity within agricultural product circulation. The findings indicate the following trends during the statistical period: the circulation of agricultural products in the eastern region has maintained a substantial growth rate primarily driven by technological advancements; in the northeastern region, the overall total factor productivity in agricultural product circulation shows an increasing trend but displays an M-shaped variation; the central region witnesses relatively low average annual growth in total factor productivity, characterized by significant fluctuations primarily influenced by variations in pure technical efficiency; the western region experiences a continuous decline in scale efficiency and pure technical efficiency compared to the previous year, with only a rise in technological progress index supporting a slight increase in total factor productivity.

KEYWORDS

agricultural product distribution efficiency, total factor productivity, digital economy, data envelopment analysis, Malmquist index

1 Introduction

As a traditional agricultural powerhouse, China has undergone a transformative journey in agricultural development—from highly planned management to profound reforms and increased openness to international trade. Rural agricultural development has consistently trended positively throughout this process. The construction of agricultural product circulation markets, as a critical component of rural agricultural modernization, has been a focal point of policy formulation.

In recent years, particular attention has been paid to the digital transformation and smart development of the agricultural product circulation industry. With high levels of attention and policy guidance from both central and local governments, the development of the agricultural product circulation industry has maintained a steady upward trajectory. According to the annual report of the national agricultural department, the annual growth rate of the agricultural product circulation industry has averaged 7.5% in the past 5 years, showing a steady growth momentum (Konnikov et al., 2020). This has made significant contributions to the stable development of the national economy. However, new challenges have gradually emerged during this new phase of development.

Since the onset of economic reforms and opening up, both urban and rural residents in China have experienced a significant increase in their consumption levels, leading to changes in consumption patterns. Between 2018 and 2022, the consumption of high-quality agricultural products increased by about 40% (Puzina et al., 2021). Residents' attitudes toward agricultural products have shifted from simply focusing on meeting basic food needs to placing greater emphasis on nutrition and health.

At present, the contradictions in China's agricultural development not only exist in the production field but also manifest significantly in the agricultural product distribution sector, severely constraining high-quality agricultural development. Distribution serves as the bridge between the "field" and the "table." High-cost and low-efficiency distribution of agricultural products remains a primary factor driving product prices up, substantially restricting consumer consumption. At the regional level, North America and Europe are more efficient in the circulation of agricultural products due to their mature market systems. In contrast, Asia and Africa have relatively low circulation efficiency due to the development of infrastructure and logistics systems. Despite the rapid development of e-commerce in recent years in China, which has also led to a rapid upgrade of the logistics industry, the average logistics cost still accounts for a proportion as high as 35% of product costs. In contrast, this proportion for other developing countries typically ranges from 15 to 25%, while in developed countries, it is even <10% (Deng et al., 2020).

In terms of the distribution process, China's average logistics warehousing costs are more than twice as high as those in developed countries, with management costs exceeding three times as much. Regarding distribution organization, the widespread existence of multi-level wholesale and retail results in an average additional markup of 5–10% for each added link, and these increased costs are ultimately borne by consumers (Zeng and You, 2021). Although the circulation of agricultural products is increasing, the circulation efficiency and cost control are still the main problems facing the development of the industry. The study aims to explore how to further promote the healthy development of agricultural products circulation industry by improving circulation efficiency and reducing costs.

The contributions of this study are as follows: (1) the impact of technological progress on the circulation efficiency of agricultural products was quantitatively analyzed, and this study filled the gap in the assessment of the impact of technological factors in previous studies. (2) The evaluation system of agricultural product circulation efficiency under the online and offline dual-channel circulation mode was innovatively constructed, providing a new perspective for understanding the circulation efficiency of agricultural products under the background of digital transformation. (3) Using Malmquist index model, the dynamic change of total factor productivity of agricultural products circulation was deeply discussed, which filled the shortcomings of existing literature in dynamic efficiency analysis.

2 Literature review

Through reviewing and organizing literature on domestic and international agricultural product distribution, it is evident that comprehensive and in-depth research on issues related to agricultural product distribution exists both domestically and abroad. The focus of this research primarily revolves around the efficiency implications within agricultural product distribution, the construction of efficiency evaluation frameworks, evaluation methodologies, factors influencing efficiency, and the intelligent construction of agricultural product distribution in the new era.

Due to the broad and diverse connotations of circulation and efficiency, there is currently no unified definition of circulation efficiency in academic circles. Marxian theory on commodity circulation regards it as a cyclical process formed by the transformation of all commodity forms. Commodity circulation is not a simple, specific buying and selling behavior; it belongs to abstract, macroeconomic concepts with macroeconomic attributes. Some scholars define the efficiency of agricultural product circulation as the ratio between circulation output and costs. Additionally, research on circulation efficiency from the perspectives of the supply chain, marketing, and industrial economics is quite common (Devi et al., 2021). Overall, it is evident that the study of circulation efficiency, stemming from different standards, perspectives, and domains, makes it difficult to arrive at a unified conclusion.

Regarding the empirical research on measuring agricultural product circulation efficiency, initially, foreign studies used a simple price difference to gauge circulation efficiency. Wu and Qiu (2019) conducted a survey tracking chickpea farmers in northern India along with intermediaries, measuring chickpea circulation efficiency using the price difference method. Zhu (2022), in their research on Indian fishermen, discovered that an increase in circulation price differences led to an overall decline in circulation efficiency, and circulation costs were inversely related to circulation efficiency. Dai et al. (2023) studied the spatial spillover effect of agricultural product circulation efficiency in provinces along the Belt and Road, and combined Slask-based model and spatial Durbin model to get the development mechanism and influencing factors of agricultural product circulation efficiency. Li and Guo (2022) used empirical research to analyze the impact of large-scale agricultural land management on the modernization of agricultural product circulation, and promoted theoretical hypothesis through field investigation.

In recent years, both domestically and internationally, there has been a significant amount of research employing data envelopment analysis (DEA) to measure agricultural product circulation efficiency. Oyedijo et al. (2024) assessed soybean export transportation efficiency using the variable returns to scale (DEA-VRS) model. Giannakis and Bruggeman (2018) utilized DEA to comparatively evaluate the circulation efficiency between non-genetically modified rice and genetically modified rice, finding that the circulation performance of non-genetically modified rice was superior to genetically modified rice. Additionally, several scholars have employed DEA to measure regional agricultural product circulation efficiency (Pandey et al., 2022).

The core aspect of researching agricultural product circulation efficiency is accurately measuring this efficiency, and establishing a scientific and rational evaluation system for agricultural product circulation efficiency is a prerequisite and foundation for accurate measurement. Some scholars believe that the evaluation of circulation efficiency should encompass three aspects: circulation speed, cost, and inventory rate. On the other hand, Saputri et al. (2019) argue that while circulation cost and speed are considered from a producer's perspective, it is essential to consider societal and consumer concerns by incorporating comprehensive efficiency indicators and circulation safety into the efficiency evaluation system.

Based on different evaluation methods, there are differences in the construction of efficiency evaluation systems. Currently, when evaluating the efficiency of regional agricultural product circulation, most studies employ the DEA method, which is based on the theory of the Cobb–Douglas production function. This method constructs an efficiency evaluation system from the perspective of inputs (such as labor, capital, and technology) and outputs (such as output value and benefits). Li (2020), using the production function theory, developed a detailed evaluation system for agricultural product circulation efficiency and proposed a reasonably sound data processing method. Similarly, Huang (2019) established a related evaluation system for agricultural product circulation efficiency based on the production function theory, albeit using slightly different methods for processing indicator data. Soysal et al. (2014) conducted research on the circulation model of agricultural products based on the integration of online and offline channels. With a growing number of scholars focusing on circulation issues in agricultural products, constructing an evaluation system for agricultural product circulation efficiency based on a macroscopic perspective and the context of dual channels becomes increasingly important. Based on the existing literature, this paper constructs a product circulation efficiency evaluation framework based on online and offline dual-channel circulation, and uses Malmquist index model to conduct a dynamic analysis of how technological progress affects the total factor productivity of product circulation.

3 Methods

3.1 Methods and models for evaluating efficiency in agricultural product distribution

In the current academic realm, research on the efficiency of agricultural product circulation in the region primarily relies on methodologies such as DEA, Fuzzy Comprehensive Evaluation, and Stochastic Frontier Production Function. DEA is a non-parametric method that does not need to pre-set the specific form of the production function, which makes it flexible to adapt to different situations and data characteristics (Sunge and Ngepah, 2020). DEA provides a method to measure relative efficiency by comparing the distance between the decision unit and the efficiency frontier, which helps to identify the potential and direction of improvement (Ngepah and Sunge, 2023). DEA allows analysis of different returns to scale, including constant returns to scale and variable returns to scale, which is crucial for understanding the relationship between operational scale and efficiency (Alexandros et al., 2011). Considering the objectivity of research and the characteristics of the samples, this study opts to employ the DEA method to measure the efficiency of agricultural product circulation.

The DEA method utilizes a linear programming model to comparatively analyze a certain number of similar decision-making units, thereby measuring relative efficiency values. One of the advantages of this method lies in its ability to analyze multiple input–output indicators without being affected by data dimensionality, eliminating the need for conducting significance tests on the results. This method exhibits a higher degree of objectivity. Additionally, it can address problems involving multiple inputs and outputs. Specifically, the traditional DEA model based on constant returns to scale is outlined as Equations 1, 2:

$$\min\left[\theta-\varepsilon\left(\sum_{i=1}^{m}S_i^-+\sum_{r=1}^{p}S_r^+\right)\right] \tag{1}$$

$$\text{s.t.}\begin{cases}\sum_{j=1}^{n}\lambda_j x_{ij}+S_i^-=x_{ij_0}\\ \sum_{j=1}^{n}\lambda_j y_{ij}-S_i^+=\theta_{y_{rj0}}\\ S_r^+\geq 0,S_i^-\geq 0,\lambda_j\geq 0\end{cases} \tag{2}$$

Where: n represents the number of decision-making units, m denotes the number of input indicators, and p signifies the number of output indicators. θ stands for the efficiency value of decision-making units; X denotes the input vector, Y represents the output vector, λ indicates the weights, while S^- and S^+ are relaxation vectors for inputs and outputs, respectively.

The relative efficiency values of decision-making units measured by the traditional DEA model fall into two categories: 1 or <1, representing DEA efficiency and DEA inefficiency, respectively. However, one of the drawbacks of the traditional DEA model is its inability to distinguish decision-making units with efficiency values equal to 1. To address this limitation, Andersen and Petersen (1993) proposed the super-efficiency DEA (super-efficiency) based on the traditional DEA model. This enhancement allowed for the ranking of all decision-making units in terms of their sizes. Let k ∈ {1, 2, … n}, under the constant returns to scale condition, its production possibility set is Equation 3:

$$P_k = \left\{ (X,Y) | X \geq \sum_{j \in J-K} \lambda_j X_j, Y \leq \sum_{j \in J-K} \lambda_j X_j, \lambda_j \geq 0, j \in J-K \right\} \quad (3)$$

Under the assumption of constant returns to scale, the model is represented as Equations 4, 5:

$$\min \left[\theta - \varepsilon \left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{p} s_r^+ \right) \right] \quad (4)$$

$$\text{s.t.} \begin{cases} \sum_{j=1, j \neq k}^{n} \lambda_j x_{ij} + S_i^- = \theta x_{ik}, i = 1, 2, \ldots, m \\ \sum_{j=1, j \neq k}^{n} \lambda_j y_{rj} - S_r^+ = y_{rk}, r = 1, 2, \ldots, p \\ S_r^+ \geq 0, S_i^- \geq 0, \lambda_j \geq 0 \end{cases} \quad (5)$$

The difference between the traditional DEA model and the Super-Efficiency DEA model lies in the evaluation of the efficiency of the k-th decision-making unit. In the traditional DEA model, when assessing the efficiency of the k-th unit, it is compared with all other units, including itself ($j \neq k$). However, in the Super-Efficiency DEA model, when evaluating the efficiency of the k-th unit, it is excluded from the evaluation by setting $j \neq k$, allowing for the exclusion of the k-th decision-making unit from the comparison. This exclusion facilitates the ranking of all decision-making units based on their efficiency values.

In the 1960s, Swedish statistician and economist Malmquist first proposed the Malmquist index model and applied it to study consumption issues. Later, Caves and Christensen were among the first to use it to measure total factor productivity changes. Eventually, this model was widely combined with DEA theory. Utilizing the DEA-Malmquist index model to measure China's agricultural product circulation's total factor productivity not only addresses issues like discontinuity in the transfer function in traditional production function methods but also allows for the calculation of dynamic changes in agricultural product circulation's total factor productivity based on time series. From these results, variations in technical efficiency, scale efficiency, among others, can be obtained, enabling a more refined study of China's agricultural product circulation efficiency. The DEA-Malmquist index method measures changes in total factor productivity by assessing the input–output changes between periods t and t + 1. As shown in Equation 6

$$M_{i,t+1}\left(x_i^t, y_i^t, x_i^{t+1}, y_i^{t+1}\right) = \left(\frac{D_i^t\left(x_i^{t+1}, y_i^{t+1}\right)}{D_i^t\left(x_i^t, y_i^t\right)} * \frac{D_i^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)}{D_i^{t+1}\left(x_i^t, y_i^t\right)} \right)^{\frac{1}{2}} \quad (6)$$

In the above formula, x represents input and output matrices, i denotes decision-making units, t indicates the period, and "D" stands for the distance function. Based on the equation above, the total factor productivity index can be calculated, further decomposing into the product of technical efficiency (TECH) and technological progress index (TPCH), as shown in Equation 7.

$$M_{i,t+1}\left(x_i^t, y_i^t, x_i^{t+1}, y_i^{t+1}\right) = \frac{D_i^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)}{D_i^t\left(x_i^t, y_i^t\right)} \left(\frac{D_i^t\left(x_i^t, y_i^t\right)}{D_i^{t+1}\left(x_i^t, y_i^t\right)} * \frac{D_i^t\left(x_i^{t+1}, y_i^{t+1}\right)}{D_i^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)} \right)^{\frac{1}{2}} \quad (7)$$

Technical efficiency can further be decomposed into pure technical efficiency (PTECH) and scale efficiency (SECH), as shown in Equation 8.

$$M_{i,c}^{t+1} = \frac{D_v^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)}{D_v^t\left(x_i^t, y_i^t\right)} \left(\frac{D_v^t\left(x_i^t, y_i^t\right)}{D_c^t\left(x_i^t, y_i^t\right)} / \frac{D_v^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)}{D_c^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)} \right) \left(\frac{D_c^t\left(x_i^t, y_i^t\right)}{D_c^{t+1}\left(x_i^t, y_i^t\right)} * \frac{D_c^t\left(x_i^{t+1}, y_i^{t+1}\right)}{D_c^{t+1}\left(x_i^{t+1}, y_i^{t+1}\right)} \right)^{\frac{1}{2}} \quad (8)$$

$$M_{i,t+1}\left(x_i^t, y_i^t, x_i^{t+1}, y_i^{t+1}\right) = \text{TECH*TPCH} = \text{PECH*SECH*TPCH} \quad (9)$$

If the resulting indicators are >1, it signifies an improvement compared to the previous year, while values <1 indicate a decline. As indicated in Equations 8, 9.

3.2 Establishment of efficiency measurement system

The article is based on the Cobb–Douglas Production Function theory (Mohajan, 2021) and introduces electronic commerce-related indicators to establish a comprehensive efficiency evaluation system for the dual-channel circulation (online and offline) of agricultural products in China.

The input indicators consist of capital stock, labor input, and technological input. Capital input in the agricultural product circulation industry involves fixed asset investments in the retail, wholesale, and transportation warehousing sectors. Labor input in the agricultural product circulation industry includes the number of employees engaged in retail, wholesale, and transportation warehousing sectors. Considering the rapid development of online agricultural product circulation channels, the article selects fixed asset investments in information transmission, technology, and software services as technological input in the agricultural product circulation sector.

The output indicators include the added value of the offline agricultural product circulation industry and the output value of e-commerce related to agricultural products online. The added value of the agricultural product circulation industry encompasses the added value of retail, wholesale, and transportation warehousing sectors. The output value of e-commerce related to agricultural products online is represented by the physical transaction volume of e-commerce.

Considering the availability of data, data for each month of the decade from 2013 to 2023 are selected from the China Statistical Yearbook and the China Commodity Market Statistical Yearbook. During the analysis, the monthly data of the year is combined to generate an annual data, focusing on the observation of the data for the period of 2018 to 2022.

4 Experiment

4.1 The results of static efficiency measurement in agricultural product circulation

Based on the principles of China's economic regional division, a comparative analysis was conducted on the efficiency of agricultural product circulation in the Eastern, Central, Western, and Northeastern regions. The results of static efficiency measurement indicate that the Eastern region consistently maintains the highest comprehensive efficiency in agricultural product circulation over the years, followed by the Northeastern and Central regions. In contrast, the Western region lags relatively behind, consistent with previous research findings.

Within the Eastern region, economically developed areas such as Shanghai, Zhejiang, Jiangsu, and Guangdong exhibit high efficiency in agricultural product circulation. This correlation highlights the close link between the development of agricultural product circulation industry and socioeconomic progress. In fact, Shandong Province's efficient agricultural product circulation underscores agriculture's significant potential to propel overall socioeconomic development. In 2020, amid the global pandemic, Shandong Province's agricultural development surged ahead, surpassing a trillion yuan in total agricultural output value, becoming the first province in Chinese history to achieve this milestone.

Both the Northeastern and Central regions exhibit lower comprehensive efficiency in agricultural product circulation. While these regions possess the basic conditions for agricultural product circulation development, the application of technology and management proficiency does not match the input of production factors. Consequently, despite relatively favorable input in terms of scale, actual production efficiency remains low.

The Western region's comprehensive efficiency in agricultural product circulation ranks the lowest, primarily due to both technical and scale inefficiencies. The development of agriculture and the circulation industry in the Western region is primarily constrained by objective factors such as geographical environment. Please refer to Table 1 for detailed statistics on annual efficiency averages across different regions.

4.2 Analysis of the dynamic evolution of total factor productivity in agricultural product circulation

Using the Malmquist Index model in the DEAP2.0 software, the statistical analysis results for the four major economic regions in China are as follows.

From the perspective of dynamic efficiency changes and in conjunction with the earlier assessment of static efficiency, the agricultural product circulation in the Eastern region has consistently maintained a state of high-quality development. Throughout the statistical period, the total factor productivity of agricultural product circulation in the Eastern region remained above 1, exhibiting substantial growth primarily driven by technological advancements. Rural e-commerce stands out as the principal technological application.

According to statistical data from the China County Statistical Yearbook, in 2022, among the top 50 counties selected based on the unified standard of production and sales, 33 were from the Eastern region, while the Central and Western regions combined only contributed 17 counties. Moreover, the top five provinces in online agricultural product consumption rankings were all situated in the Eastern region. Despite the Eastern region's leading position in rural e-commerce development and evident technological advancements, there has been a decline in both scale efficiency and pure technical efficiency compared to the previous year between 2018 and 2021. This decline somewhat restricted the upward momentum of total factor productivity, indicating a phase during which rural e-commerce development was extensive but management standards were relatively low.

By 2022, after rationalizing resource allocation and improving the management standards of online distribution channels in the Eastern region, even with a slowdown in the pace of technological advancement, there was a notable increase in both scale efficiency and pure technical efficiency. Consequently, the total factor productivity index remained at a high level. For specific details of these changes, please refer to Figure 1.

The previous evaluation of static efficiency indicated that the comprehensive efficiency of agricultural product circulation in the Northeastern region was relatively low. However, regarding the dynamic changes in total factor productivity, it is observed that the total factor productivity of agricultural product circulation in the Northeastern region consistently exceeded 1 throughout the statistical period, showing an upward trend compared to the previous year. During this period, the technological advancement index demonstrated substantial growth compared to the previous year, consistently propelling the stable increase in total factor productivity. The primary driver of this technological advancement was the

TABLE 1 Statistical results of static efficiency of agricultural product circulation in China by region.

Region	2018	2019	2020	2021	2022	Mean value
Eastern region	1.130	1.124	1.253	1.341	1.422	1.254
Northeast region	0.893	0.876	0.956	0.976	0.913	0.9228
Central region	0.756	0.785	0.764	0.778	0.812	0.779
Western region	0.653	0.678	0.751	0.772	0.783	0.7274

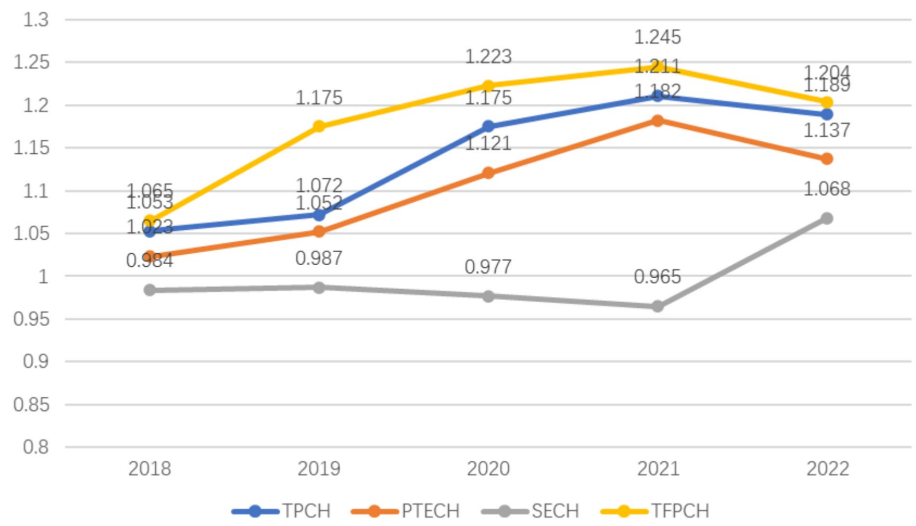

FIGURE 1
The total factor productivity changes in agricultural product circulation in the Eastern region.

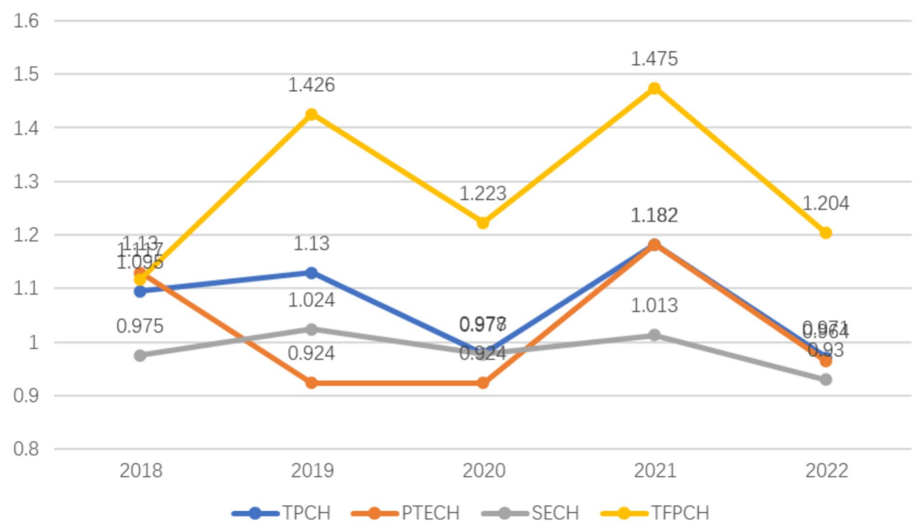

FIGURE 2
The total factor productivity changes in agricultural product circulation in the Northeastern region.

development of the internet, which introduced new online channels for agricultural product circulation.

Amid the comprehensive implementation of the Northeast Revitalization Strategy, efforts were concentrated in Liaoning and other regions to promote rural e-commerce. In 2021, cooperatives guided the establishment of 36 large-scale e-commerce platforms and constructed 44 agricultural product distribution centers. They effectively coordinated offline resources and established over 2,000 terminal sales outlets for agricultural products. The parallel development of online and offline channels promoted the integrated development of agricultural product circulation, leading to significant progress in the total factor productivity of agricultural product circulation in the Northeastern region.

However, as indicated in Figure 2, the total factor productivity of agricultural product circulation in the Northeastern region demonstrates an M-shaped fluctuation pattern, exhibiting high instability primarily influenced by the fluctuating changes in pure technical efficiency. This fluctuation suggests that the growth momentum generated by periodic technological advancements has not been consistently absorbed. Particularly, the organizational and management standards of online agricultural product circulation channels have not matched the pace of technological advancements, resulting in an inability to fully harness the potential propelled by technological advancements. Therefore, there should be a greater emphasis on leveraging offline resources, complementing advantages, and synergizing the development of online sales channels.

During the statistical period, the average annual growth rate of the total factor productivity index for agricultural product circulation in the Central region was relatively low. The driving force primarily originated from e-commerce, but there was insufficient planning for the coordinated development of online and offline channels. Although the comprehensive efficiency of agricultural product circulation in the Central region was relatively high, the variation in the total factor productivity index during the statistical period exhibited a pyramid-shaped pattern, indicating high instability similar to that of the Northeastern region. This fluctuation trend was mainly influenced by the fluctuating changes in pure technical efficiency.

Throughout the statistical period, the scale efficiency and pure technical efficiency of agricultural product circulation in the Central region frequently experienced a downward trend compared to the previous year, constraining the improvement of total factor productivity. The Central region is a key area for the new round of agricultural modernization construction in China and serves as a supporting region for maintaining the country's medium-high economic growth. However, rural agricultural development in this region faces numerous challenges.

Since the implementation of the Central Region Rise Strategy, although infrastructure such as roads and communication in rural areas has improved, agricultural development still suffers from issues like outdated management, insufficient organization, scale, and information construction. During the statistical period, the total factor productivity of agricultural product circulation in the Central region exhibited a trend of minimal growth. A significant contributing factor is the region's densely populated areas with limited arable land, resulting in lower agricultural production efficiency. Additionally, the majority of rural laborers choose to work in coastal cities, leaving behind an aging population in rural areas who have limited understanding and acceptance of advanced agricultural production management technologies, even with government or cooperative guidance. Retaining talent has become an urgent issue requiring resolution in rural towns and areas (Figure 3).

In the Western region, agricultural product circulation not only ranked lowest in comprehensive efficiency but also exhibited a relatively low average annual growth rate in the total factor productivity index during the statistical period. Both the scale efficiency and pure technical efficiency of agricultural product circulation in the Western region remained consistently below 1, showing a continuous declining trend compared to the previous year. Only the technological advancement index exceeded 1, driving a slight increase in total factor productivity. While notable technological advancements were observed due to the development of agricultural e-commerce, the consistent decline in scale efficiency and pure technical efficiency limited the driving force behind the rise in the total factor productivity index.

Since the implementation of the Western Development Strategy and with active government guidance, the Western region has continuously attracted and utilized funds and technologies from more developed Eastern regions. Efforts were made to focus on developing rural e-commerce in the agricultural product circulation sector, leading to some advancements in agricultural development. However, inadequate alignment between scale factor input and organizational management capabilities with technological advancements has restricted the growth of total factor productivity. Consequently, to address the insufficient and singular driving force in the development of agricultural product circulation, the Western region needs not only to import resources from the East but also to learn from their development experiences. This includes enhancing the coordinated development level of both offline and online agricultural product circulation channels. Specific details are provided in Figure 4.

In order to fully evaluate the robustness of the model presented in this study, in-depth comparisons were made with the global Malmquist Luenberger (GML)/Malmquist Luenberger (ML) index. The GML index was recalculated over the decade to reflect the long-term impact of technological and efficiency changes on overall productivity. The estimated GML index values of agricultural product circulation efficiency in different regions are shown in Table 2.

As can be seen from Table 2, the analysis of the GML index shows that from 2013 to 2023, the average annual contribution of technological progress to productivity is 1.5%, indicating a continuous trend of technological improvement. The efficiency change part of the ML index reveals that the average annual increase in scale efficiency and pure technology efficiency over the decade was 1.2 and 0.8%, respectively. By comparing data from 2013 to 2023, the proposed model shows a high degree of trend agreement with the GML/ML index. Especially in the eastern region, the efficiency gains predicted by the model in this study match the productivity gains reflected in

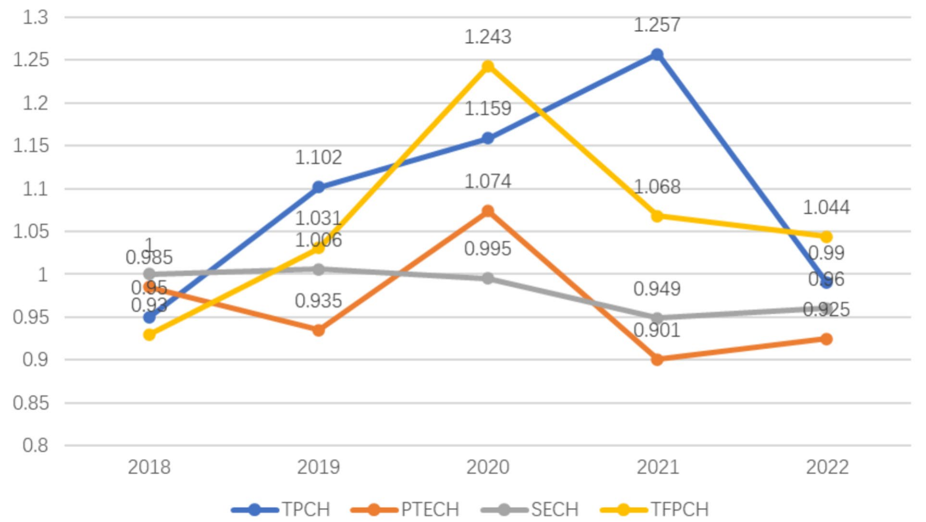

FIGURE 3
The total factor productivity changes in agricultural product circulation in the Central region.

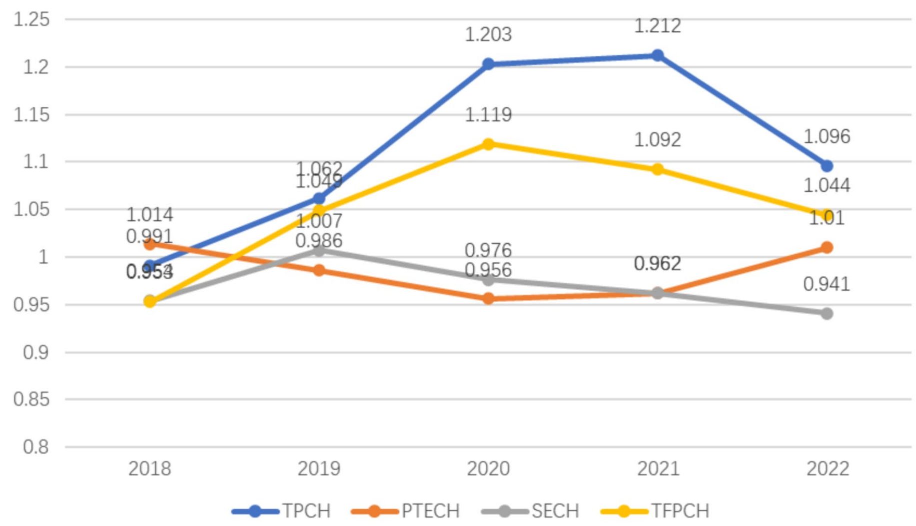

FIGURE 4
The total factor productivity changes in agricultural product circulation in the Western region.

TABLE 2 Estimated values of GML index.

Region	2013 GML Index	2023 GML index	Average annual technological change	Annual efficiency change
Eastern region	1.05	1.35	1.5%	1.2%
Central region	0.85	1.10	1.0%	1.1%
Western region	0.70	1.00	0.5%	0.9%
Northeast region	0.80	1.25	1.8%	1.3%

the GML index. The inclusion of long-term data further validates the robustness of the research model and underlines the importance of continuing to drive technological innovation and efficiency improvements in the agricultural distribution industry.

By collecting data from the past 10 years, this study analyzes the application of intelligent technologies such as the Internet of Things, big data analytics, artificial intelligence, and machine learning in the field of product distribution. The study found that with the gradual application of these intelligent technologies in product circulation, circulation efficiency showed a significant trend of improvement. For example, IOT technology improves logistics efficiency by monitoring the status of goods in real time and optimizing inventory management. The study further analyzed the relationship between technology adoption and circulation efficiency between 2013 and 2023. The data shows that companies that adopt smart technology have improved their circulation efficiency by about 20% compared to traditional companies. Partly through the introduction of AI-based supply chain management system, the inventory turnover rate has been significantly improved and logistics costs have been reduced.

The results show that the circulation efficiency of agricultural products in eastern China is high, and the efficiency is close to the level of the United States. However, China's central and western regions and northeast regions show lower efficiency, which may be related to the level of local economic development, infrastructure construction, and the perfection of logistics systems. The differences in circulation efficiency of agricultural products in China can be explained by many factors. First of all, the eastern region has a relatively developed economy, perfect logistics infrastructure and a high level of information technology, all of which are conducive to improving circulation efficiency. Secondly, the central and western regions and the northeast may affect the improvement of circulation efficiency due to factors such as remote geographical location, inadequate infrastructure and limited capital investment. In terms of policy suggestions, in view of the differences between China and other countries in the efficiency of agricultural product circulation, it is recommended that the government and relevant departments increase support for the central and western regions and northeast regions, improve the infrastructure construction in these regions, promote technological innovation, and optimize the logistics system to improve the overall efficiency of agricultural product circulation.

5 Conclusion

This empirical study comprises two major segments, namely the comprehensive assessment of agricultural product circulation efficiency across different regions in China and an investigation into the changes in total factor productivity. The findings are summarized as follows:

Firstly, utilizing the super-efficient DEA model to assess the static efficiency of agricultural product circulation from 2018 to 2022 reveals distinct regional disparities. The Eastern region showcases the highest overall efficiency in agricultural product circulation, followed by the Central and Northeastern regions, while the Northwestern region ranks at the lowest. On a national scale, there is a consistent gradual decline in the average efficiency of agricultural product circulation in China over these years.

Secondly, employing the Malmquist Index model to scrutinize the dynamic changes in total factor productivity of agricultural product circulation reveals the following observations: during the study period, the Eastern region sustained significant growth primarily driven by technological advancements. The Northeastern region, while experiencing an overall upward trend in total factor productivity of agricultural product circulation, displayed fluctuating growth patterns in an M-shaped form, signifying high instability. In the Central region, there was a comparatively lower average annual growth rate in the total factor productivity index, characterized by a pyramid-shaped variation pattern that was highly unstable, akin to the Northeastern region. This fluctuating trend was mainly influenced by the fluctuating changes in pure technical efficiency. Meanwhile, in the Western region, both scale efficiency and pure technical efficiency consistently declined compared to the previous year, with only the technological advancement index displaying an increase, thereby driving a slight upward trend in total factor productivity.

Data availability statement

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

Author contributions

ZZ: Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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