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The impact of land consolidation on rapeseed cost efficiency in China: policy implications for sustainable land use and food security

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The relationship between farm size expansion and efficiency is a key topic in agricultural economics, especially for achieving sustainable land use and food security. While existing literature focuses on land productivity, technical efficiency, and total factor productivity, the link between farm size and cost efficiency remains less explored. Cost efficiency is a critical indicator of production effectiveness and directly impacts agricultural sustainability and food security. This paper analyzes how farm size expansion affects the cost efficiency of Chinese rapeseed production, with a particular emphasis on sustainable agricultural production and food security. Our findings indicate an average cost efficiency of 0.740 for rapeseed in China, suggesting potential for improvement. We observe an inverted U-shaped relationship between farm size and rapeseed cost efficiency, with variations based on regional and topographic conditions. Optimal rapeseed farm size is between 10 and 30 mu in eastern and central China, and smaller than 10 mu in western China. Interestingly, in central China and plains regions, larger farm sizes have a less negative impact on cost efficiency. Finally, increasing plot size positively moderates the relationship between farm size and rapeseed cost efficiency, suggesting benefits from expanding both plot and farm sizes simultaneously. These findings provide empirical evidence to inform policy decisions related to sustainable land use, cost-efficient agriculture, and food security.

KEYWORDS

farm size, food security, sustainable land use, China, cost efficiency

1 Introduction

China's agricultural sector is grappling with several significant challenges that are unique to its situation. These include a large population that demands a steady and secure food supply, scarce arable land that limits the extent to which food can be produced domestically, a predominance of small-scale farming that complicates efforts to increase efficiency, and severe land fragmentation that hinders the effective use of modern agricultural technologies (Tan et al., 2006; Xu et al., 2020). To address land fragmentation and promote efficient mechanization, the government has implemented policies focused on consolidating land management rights, clarifying property rights, and stimulating a more active land transaction market (Fleisher and Liu, 1992; Liu Z. et al., 2017; Gao et al., 2020). These policies are designed to encourage the growth of farm sizes, both in terms of operational scale and the physical size of plots, as a means of achieving economies of scale (Liang et al., 2020; Guan et al., 2023). However, the persistence of land fragmentation poses a significant barrier to realizing the full benefits of scale, as it can prevent the efficient deployment of mechanized farming methods, thus affecting both productivity and economic returns (Guo et al., 2019; Razzaq et al., 2022; Qi et al., 2023). The consolidation of land into larger, more contiguous plots is seen as a critical step toward enabling the widespread adoption of mechanization (Zhang and Luo, 2020), which can lead to significant improvements in input-use efficiency and a reduction in production costs. This paper aims to investigate the impact of plot size expansion on the cost efficiency of Chinese rapeseed production, with the goal of providing valuable insights that can inform sustainable land use and food security policies.

The relationship between farm size and various forms of agricultural efficiency has been a subject of extensive research (Razzaq et al., 2019). However, findings have been mixed. On one hand, some studies have identified a negative correlation between farm size and technical efficiency, suggesting that smaller farms might be able to use their resources more effectively than their larger counterparts (Lau and Yotopoulos, 1971; Liu and Cai, 2013). This perspective is supported by data indicating an inverse relationship between farm size and the technical efficiency of grain production. On the other hand, a body of research argues for a positive correlation, with larger farms displaying higher levels of technical efficiency and making better use of machinery, which, in turn, boosts overall productivity (Bravo-Ureta and Rieger, 1991; Liu and Cai, 2013; Zhang et al., 2013; Geng et al., 2014; Liu F. et al., 2023). This view is further supported by studies showing a positive link between farm size and agricultural productivity on a regional and national level over time (Yao and Hamori, 2019; Helfand and Taylor, 2021). Despite the wealth of research on this topic, the specific relationship between farm size—particularly in terms of plot size—and cost efficiency has received less attention. On the one hand, the transfer of agricultural land, the size of the plot, and the scale of the operation can all introduce variability that should not be ignored (Zhang and Luo, 2020). On the other hand, cost efficiency reflects the ability to achieve an increase in output within a given cost constraint or a reduction in costs within a given output constraint. This aligns with the Chinese government's original intention to support moderate-scale operations (Wang et al., 2019). At the same time, cost efficiency is a critical factor in determining the economic sustainability of agricultural practices, making it an important area of study for those concerned with the long-term viability of food production systems.

In 2020, China was one of the world's leading producers of rapeseed, with a total planted area of nearly 6,764,700 hectares and an impressive output of 14,049,100 tons. This remarkable achievement positioned China as the second-largest producer of rapeseed globally, reflecting the country's strong agricultural capabilities and commitment to meeting the growing demand for this valuable crop. This study investigates the specific impact of increasing plot size on the cost efficiency of Chinese rapeseed production, addressing an important gap in the literature. Understanding how plot-level dynamics interact with overall farm size expansion is essential for developing policies that promote cost-effective agricultural practices. This research emphasizes the significance of land consolidation for achieving sustainable agriculture. By analyzing detailed farmer microdata, we aim to explore the relationship between farm size, plot size, and oilseed rape production efficiency, and to identify solutions to improve oilseed rape production efficiency, thereby promoting sustainable agricultural development and food security in China. Ultimately, our findings will provide empirical evidence to inform policy decisions aimed at ensuring both a stable food supply and environmentally responsible land management practices.

Considering sustainable land use and food security, this paper measures the cost efficiency of rapeseed production using stochastic frontier analysis. It decomposes cost efficiency into technical and allocative efficiency using micro research data (2018–2021) from fixed observation points within the Chinese government's rapeseed industrial technology system. A Tobit model analyzes factors influencing rapeseed production cost efficiency along with its heterogeneity. Finally, the study examines the role of plot size within the impact that farmer operational scale has on rapeseed production cost efficiency.

2 Materials and methods

2.1 Methods

2.1.1 Measuring rapeseed production cost efficiency for sustainable agriculture and food security

A rigorous assessment of rapeseed production cost efficiency is the foundation of this empirical research. We employ the stochastic frontier analysis (SFA) approach for its ability to decompose cost efficiency effectively (Ozkan et al., 2009) and its suitability for the agricultural sector, where uncertainty is prevalent (Koop et al., 1999; Belotti et al., 2013). The SFA method necessitates the specification of function types, which include the stochastic frontier production function, cost function, and profit function, chosen based on the variables under examination (Battese and Coelli, 1995). For our analysis, the stochastic frontier cost function is constructed to assess the cost efficiency of rapeseed production in China and identify factors influencing it. The stochastic frontier cost function is represented as:

$$C_{it} = f\left(P_{it}, Y_{it}, \beta\right) + v_{it} + u_{it} \quad (1)$$

where $i = 1, 2, \ldots, N$; $t = 1, 2, \ldots, T$. P_{it} represents input factor prices, Y_{it} is the output, C_{it} denotes total cost, and β are the parameters to be estimated. The error term $\varepsilon_{it} = v_{it} + \mu_{it}$ is the stochastic disturbance term, which consists of two components that satisfy $\mathrm{cov}(\mu_{it}, v_{it}) = 0$ and $v_{it} \sim i.i.dN\left(0, \sigma_v^2\right)$. The term μ_{it} refers to the cost inefficiency factor, which is conventionally modeled as a non-negative distribution, i.e., $\mu_{it} \sim i.i.dN^+\left(it, \sigma^2\right)$, indicating that inefficiencies contribute to an increase in production costs. The coefficient of μ_{it} is positive, reflecting the direct impact of inefficiencies on elevating production expenses (Battese and Coelli, 1995).

The model for analyzing the cost efficiency of rapeseed production incorporates both the Cobb–Douglas (C-D) and Translog functions, with specific reference to Campos et al. (2022) for their foundational frameworks. The choice of the C-D function is motivated by three main factors: its inherent property of self-duality, the transparency and significance of its parameter estimations for economic interpretation, and its straightforward application in disentangling efficiency (Musau et al., 2021; Octrina and Mariam, 2021). Given these advantages, our study employs the C-D function to formulate the stochastic frontier cost function model. This model acknowledges the behavior of input factor prices through a non-decreasing, linearly chi-squared, and concave pattern, adhering to the condition that $\sum\beta_j = 1$. Substituting this constraint into Equation (1) leads to a refined expression of the stochastic frontier cost function under the chi-squared constraint as follows:

$$\ln\left(C_{it} / P_{kit}\right) = \beta_0 + \sum_{j=1}^{k-1}\beta_j \ln\left(P_{jit} / P_{kit}\right) + \beta_y \ln\left(Y_{it}\right) + \gamma t + v_{it} + u_{it} \quad (2)$$

For simplification, we define $c_{it}=(C_{it}/P_{kit})$, $w_{jit}=\ln(P_{jit}/P_{kit})$, $y_{it}=\ln(Y_{it})$, and

$$C_{it} = \beta_0 + \sum_{j=1}^{k-1}\beta_j w_{jit} + \beta_y y_{it} + \gamma t + v_{it} + u_{it} \quad (3)$$

The term μ_{it} is the cost inefficiency term and the mean of its distribution can be expressed as a function of the factors influencing cost inefficiency. The cost inefficiency function is:

$$\bar{\omega}_{it} = \alpha + S\delta + Z\varphi + \xi \quad (4)$$

In Equation (4), S symbolizes the scale of land operation by the farmer; Z includes other control variables, with α, δ, and φ as the parameters to be estimated, and ξ as the random perturbation term.

Following Aigner et al. (1977), the structure of the cost inefficiency function allows for empirical testing, facilitating the separation of cost efficiency into technical efficiency and allocative efficiency. Technical efficiency is computed by:

$$CTE_{it} = \exp\left(-\mu_{it} / r\right) \quad (5)$$

And allocative efficiency is determined through:

$$CAE_{it} = \exp\left(\ln r - A_{it}\right) \quad (6)$$

Hence, the formula to calculate cost efficiency merges these efficiencies:

$$CE_{it} = CTE_{it} \times CAE_{it} = \exp\left(\ln r - A_{it} - \mu_{it} / r\right) \quad (7)$$

In Equation (7), r denotes the economies of scale, and A denotes the function representing the random error term introduced by allocative inefficiencies, as detailed by Schmidt and Lovell (1979). This approach enables a comprehensive analysis of rapeseed production cost efficiency, emphasizing the importance of both farm size and the efficient allocation of resources for achieving both economic viability and sustainable agricultural practices.

2.1.2 Methods for analyzing the impact of land consolidation on cost efficiency

To investigate the relationship between land consolidation and the cost efficiency of rapeseed production in China, we employ the Tobit regression model. The Tobit model is particularly suited for this analysis due to its ability to handle censored data, which is common in efficiency studies where the efficiency score is bounded. This approach aligns with recent methodologies employed by Xue et al. (2021) and Chen and Wang (2022), ensuring consistency within the field.

The model is specified as follows:

$$CE_i = \begin{cases} \beta^T X_{it} + \varepsilon_{it}, & \beta^T X_{it} + \varepsilon_{it} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

In Equation (8), CE_{it} represents the cost efficiency score for rapeseed production. The variable X_{it} includes a vector of explanatory factors that potentially influence cost efficiency. These factors incorporate household head characteristics, the sown area dedicated to rapeseed, terrain features, income from subsidies, the proportion of labor hired, and the rate of land transfers. The term β^T denotes the vector of coefficients for these variables, and ε is the random error component.

2.2 Data

The foundational data for this analysis is derived from the detailed records of individual farmers within the National Rapeseed Industry Technology System, spanning from 2018 through 2021. This comprehensive dataset includes observations from 3,208 farming households situated across a wide geographical span of 14 provinces and 87 counties, specifically within China's predominant winter rapeseed producing regions. Particularly, these regions are responsible for the majority—90%—of rapeseed sown area nationally, underscoring their significance in the overall production landscape. The National Rapeseed Industry Technology System, a collaborative initiative by the Ministry of Finance and the former Ministry of Agriculture, established 30 comprehensive experimental stations dedicated to rapeseed research across China. These stations, strategically placed across the country's rapeseed belts, play a critical role in continuously monitoring and recording the economic performance of rapeseed cultivation, thereby providing a rich dataset for analysis. Staffed primarily by members of provincial agricultural research institutes, agricultural and rural bureaus, and county-level agricultural extension organizations, these stations leverage expertise in agricultural economic management and established relationships with farmers to ensure accurate and reliable micro-research data. The survey employed stratified random sampling methods. Descriptive statistics indicate that core sample data variables align closely with national macro-statistical values, demonstrating the representativeness of the data source. The study's geographic focus is depicted in Figure 1.

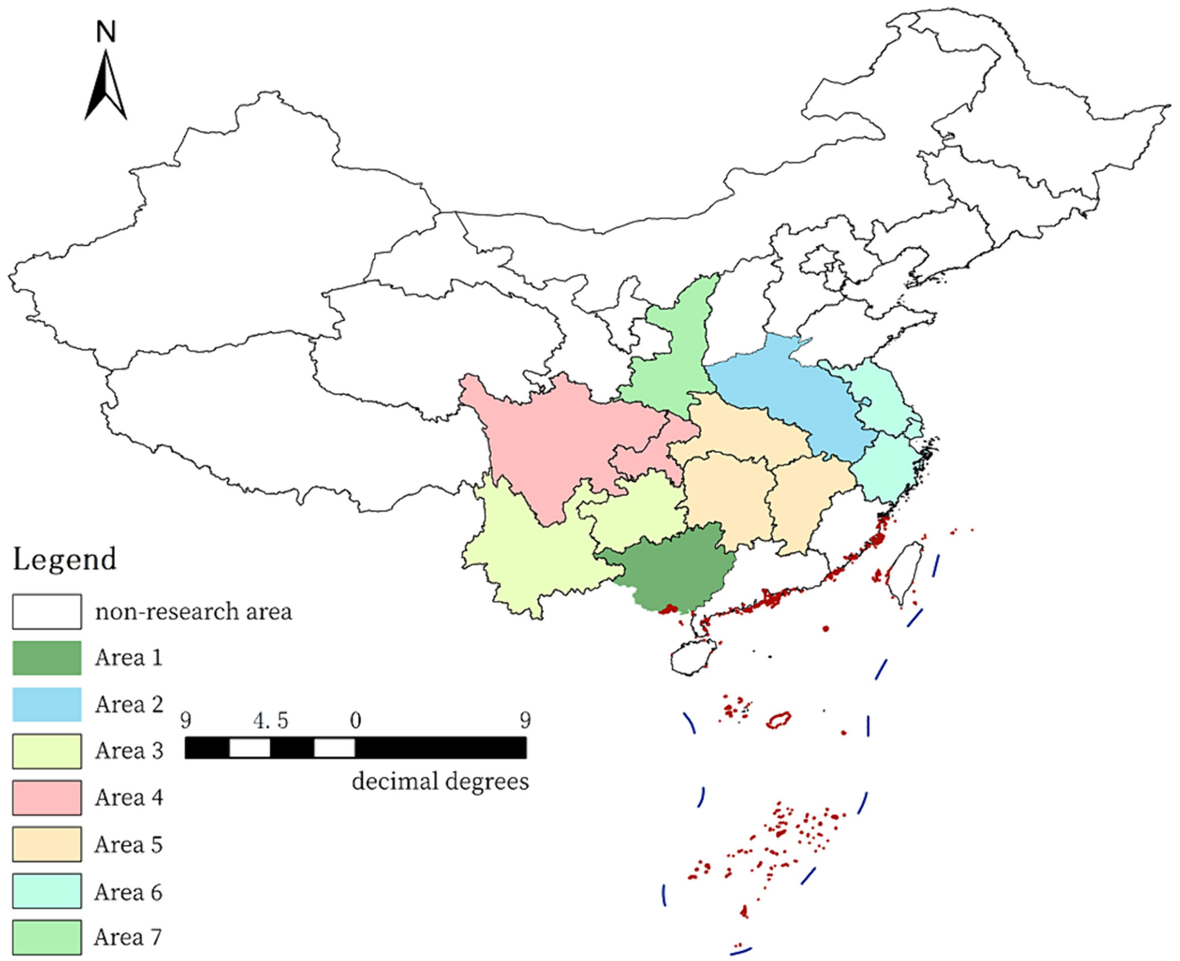

FIGURE 1
Distribution Map of the Main Winter Rapeseed Producing Areas in China. Area 1: South China coastal winter rapeseed production area, including Guangxi. Area 2: Huanghuai Plain winter rapeseed production area, including Anhui and Henan. Area 3: Yunnan-Guizhou Plateau winter rapeseed production area, including Yunnan and Guizhou. Area 4: Sichuan Basin winter rapeseed production area, including Sichuan, Chongqing. Area 5: winter rapeseed production area in the middle reaches of Yangtze River, including Hubei, Hunan and Jiangxi. Area 6: winter rapeseed production area in the lower reaches of the Yangtze River, including Zhejiang, Jiangsu and Shanghai. Area 7: Loess Plateau winter rapeseed production area, including Shaanxi.

The analysis undertaken in this paper rigorously evaluates data trends from 2018 to 2021 to discern patterns at the national level as well as across the eastern, central, and western regions of China. After excluding data that did not meet the stringent criteria required for this empirical investigation, the study proceeded with a robust sample of 3,088 farm households. This refined sample size, which represents a 96.26% validity rate from the original dataset, ensures a high degree of reliability and accuracy in the findings presented.

2.3 Variables definitions

2.3.1 Dependent variable

The primary variable of interest, rapeseed cost efficiency, is derived using the Stochastic Frontier Analysis (SFA) approach. This method necessitates the meticulous selection of both input and output variables to accurately compute cost efficiency. In alignment with established research, the output variable here is defined as the total cost incurred by farmers, which includes the costs associated with seeds, fertilizers, labor, land usage, and machinery operations. Input variables are characterized by the total production output of rapeseed and the costs of essential inputs: namely, the price per unit area for seeds, fertilizers, machinery, labor wages per day, land transfer costs per unit area, and other related expenses. To adjust for inflation or deflation over time, price variables were normalized using a relevant price index. Specifically, we used the Agricultural Production Material Price Index (APMPI) with 2018 as the base year to deflate the indicators.

2.3.2 Core explanatory variables

The study places particular emphasis on farm size as its core explanatory variable. Farm size is evaluated through two principal measures: the total land area and the specific area sown with rapeseed. Given that the sown area provides a closer reflection of the operational conditions for rapeseed cultivation, it is utilized as the primary measure of farm size. Further, to explore the aspect of land fragmentation, this study incorporates the concept of plot size, defined by the ratio of total sown area to the number of plots owned by a household.

TABLE 1 Descriptive statistics of variables.

Variables	Definitions/units	Averages	Standard deviation	Minimum	Maximum
Total output	kg	3563.53	10639.02	40.00	70300.00
Seed price	Yuan/mu	17.09	13.59	5.48	51.90
Fertilizer price	Yuan/mu	99.17	59.75	21.20	288
Machinery price	Yuan/mu	52.16	53.07	0	187.23
Labor price	Yuan/workday	95.41	22.28	53.14	150
Land price	Yuan/mu	432.52	246.25	26.50	1011.75
Other price	Yuan/mu	26.48	126.13	0	6672.22
Age	Year	60.35	9.31	36	77
Gender	0 = female, 1 = male	0.90	0.28	0	1
Education	Year	7.56	2.726	0	16
Health status	1 = worse, 2 = same, 3 = better	2.41	0.562	1	3
Farm size	Mu	21.09	94.49	0.2	2,640
Topography	0 = non-plain, 1 = plain	0.32	0.467	0	1
Distance to markets	km	3.49	2.636	0.2	20
Distance to agricultural institutions	km	4.50	3.719	0.1	30
Subsidies	Yuan	3223.83	12604.66	0	78,000
Hired worker weight	%	0.10	0.261	0	1.5
Number of parcels	Lump	20.21	69.07	1	765
Land transfer rate	%	0.27	0.37	0	1
Time dummy variables	1 = 2018, 2 = 2019, 3 = 2020, 4 = 2021	2.51	1.12	1	4
Regional dummy variables	1 = East, 2 = Central, 3 = West	2.11	0.724	1	3

2.3.3 Control variables

To account for the influence of various factors on rapeseed production cost efficiency, this study integrates several control variables, drawing on the methodology of Zhang et al. (2022). The variables include (1) age, defined as the difference between the survey year and the birth year of the decision-maker, serving as an indicator of experience and potentially, human capital; (2) gender, coded as 0 for females and 1 for males, to examine the role of gender dynamics in farming efficiency; (3) education, measured by the highest level of schooling completed, with categories ranging from 6 years for elementary education to 16 years for undergraduate studies, reflecting the decision-maker's educational background; (4) health status, assessed on a scale where 1 indicates differential health compared to peers, 2 the same, and 3 better health, to gauge the potential impact of health on productivity; (5) topography, with a binary coding of 0 for non-plain areas and 1 for plain areas, to consider the geographical influences on farming practices; (6) subsidies, including various forms of governmental support such as land, operation, machinery, and cropland protection subsidies, which affect the economic aspects of rapeseed farming; (7) hired worker weight, the ratio of hired laborers to the total labor force, to understand the reliance on external labor; (8) distance to markets and (9) agricultural institutions, both measured in kilometers, to factor in the accessibility of essential services and markets; (10) the number of parcels, to explore the effects of land fragmentation; (11) land transfer rate, the proportion of leased land to total farmed land, to assess the impact of land mobility on efficiency; (12) regional and (13) time dummy variables, included to capture the variability in cost efficiency across different locations and periods. Analysis of these variables provides a comprehensive understanding of the factors influencing cost efficiency in rapeseed production, with detailed statistics presented in Table 1.

3 Results and discussion

3.1 Sustainable cost efficiency measurement, decomposition, and heterogeneity analysis

In this section, we present the results of the cost efficiency analysis. We examine the individual components of cost efficiency and present the findings of the heterogeneity analysis. These findings provide a more comprehensive understanding of the current state of rapeseed production efficiency and its implications for sustainability and food security. We utilize Equations 1–8 from the methodology to calculate cost efficiency, technical efficiency, and allocative efficiency. The results are summarized in Table 2, which includes classification characteristics based on time.

TABLE 2 Cost efficiency of rapeseed production at different periods.

Variables	2018	2019	2020	2021	Full sample
Cost efficiency	0.601	0606	0.735	0.733	0.670
Technical efficiency	0.685	0.683	0.794	0.793	0.740
Allocation efficiency	0.867	0.857	0.915	0.916	0.889

TABLE 3 Cost efficiency of rapeseed production at different scales.

Variables	<10 mu	10–30 mu	30–50 mu	50–100 mu	100–200 mu	>200 mu
Cost efficiency	0.691	0.700	0.659	0.610	0.572	0.510
Technical efficiency	0.759	0.765	0.730	0.687	0.655	0.597
Allocation efficiency	0.900	0.902	0.886	0.862	0.847	0.808

The results show that, overall, the average value of cost efficiency of rapeseed farmers is 0.670, showing there is a significant inefficiency and room for improvement. The actual cost of rapeseed production for farmers has a large deviation from the frontier cost, and there is still a 33% efficiency loss compared with the minimum cost. There is still a large room for improvement in cost efficiency. From the decomposition value of cost efficiency, the average values of technical efficiency and allocation efficiency are 0.740 and 0.889, respectively, which indicates that technical efficiency and allocation efficiency jointly affect cost efficiency improvement. In addition, as seen in the results of Table 2, technical efficiency is marginally increasing over time. Therefore, the key point to improve the cost efficiency of rapeseed production lies in the improvement of individual farmers' business practices and the scientific adoption of new technologies and equipment (Zhang and Zhou, 2019).

The findings suggest that rapeseed farmers have the potential to improve their cost efficiency significantly. The average cost efficiency of rapeseed farmers is 0.670, indicating that there is room for improvement. The actual cost of rapeseed production for farmers is significantly higher than the minimum cost, indicating a 33% efficiency loss. This loss can be attributed to both technical inefficiency and allocative inefficiency. Technical efficiency refers to the ability of farmers to produce rapeseed at the lowest possible cost using the available resources, while allocative efficiency refers to the ability of farmers to allocate resources optimally among different inputs. The results in Table 2 also show that technical efficiency has improved over time, suggesting that farmers are becoming more efficient in their production practices. To further improve cost efficiency, farmers should focus on improving both technical efficiency and allocative efficiency. This can be achieved by adopting new technologies and equipment, improving management practices, and optimizing resource allocation (Zhang and Zhou, 2019).

Within the temporal dimension, there appears to have been a substantial fluctuation in cost efficiency during the year 2020, which may be attributed to the emergence of the COVID-19 pandemic. Farmers engaged in agricultural labor less frequently due to the pandemic, thereby affording them more time for field management. This conclusion aligns with the postulations of Zhang et al. (2021) and is further supported by the implementation of national policies providing subsidies for machinery purchases, which resulted in an increased utilization of agricultural machinery services. As mechanization progresses, reliance on costly labor decreases, potentially enabling larger farm sizes (Gardner, 2002; Zhou et al., 2015; Sang et al., 2023). Consequently, rapeseed production became significantly more mechanized compared to the corresponding period in preceding years, leading to an unexpected increase in cost efficiency.

Similarly, the cost-effectiveness of farmers' production at various planting scales was analyzed. Table 3 presents the results. According to the six scale intervals, the cost efficiency of rapeseed production follows an inverted U-shaped pattern as the planting size increases, which is consistent with the findings of previous studies (Liu Q. et al., 2017; Liu et al., 2018; Zhao et al., 2021; Zhang et al., 2022). There exists an optimal moderate scale of operation for rapeseed production, and the cost efficiency reaches its peak when the scale is between 10 and 30 mu. However, if the planting scale continues to increase beyond a certain interval, the cost efficiency of rapeseed production exhibits a "cliff-like" downward trend. This suggests that overstretching the scale of operation by farmers will result in decreased cost-effectiveness and profitability of rapeseed production. Notably, the cost efficiency is the lowest for households with scales exceeding 200 mu.

Two possible reasons can explain this phenomenon. On the one hand, as the scale of farmers' operations expands and the use of hired labor increases, not only do supervision and management costs rise, but farmers also need to pay wages in the labor market according to the market price. On the other hand, when the scale of farmers' operation reaches a certain critical value, the management of farmland by farmers also reaches the optimum. However, as the scale increases further, farmers may lack sufficient energy to manage the farmland effectively. Additionally, the infrastructure, agronomic training, personnel management, and factor marketization reforms of the farmland may lag behind the moderate-scale development process, which reduces the cost-efficiency of rapeseed cultivation. Furthermore, the study results reveal significant differences in cost efficiency, technical efficiency, and allocation efficiency among the six scales. It is also observed that the technical efficiency of rapeseed production exhibits an inverted U-shaped pattern as the scale of farmers' operations expands, reaching its highest point when the scale is between 10 and 30 mu. However, the relationship between the scale of farmers' operations and allocation efficiency is less pronounced compared to technical efficiency. In summary, farmers should not blindly expand their scale but rather choose a moderate-scale planting approach based on local resource endowments and their own management capabilities.

TABLE 4 Results of the effect of farm size expansion on efficiency.

Variables	Model 1	Model 2	Model 3
	Cost efficiency	Technical efficiency	Allocation efficiency
Farm size	−0.0266*** (0.0030)	−0.0241*** (0.0020)	−0.0146*** (0.0010)
Gender	−0.0153 (0.0090)	−0.0140* (0.0080)	−0.0072 (0.0050)
Age	−0.0000 (0.0000)	−0.0000 (0.0000)	−0.0000 (0.0000)
Education	0.0008 (0.0010)	0.0007 (0.0010)	0.0004 (0.0010)
Health status	0.0103** (0.0050)	0.0092** (0.0040)	0.0059** (0.0030)
Distance to markets	−0.0072*** (0.0010)	−0.0056*** (0.0010)	−0.0020*** (0.0010)
Distance to agricultural institutions	0.0057*** (0.0010)	0.00460*** (0.0010)	0.0017*** (0.0010)
Hired worker weight	−0.0599*** (0.0140)	−0.0477*** (0.013)	−0.0153* (0.0080)
Topography	0.0317*** (0.0060)	0.0259*** (0.0050)	0.0106*** (0.0030)
Subsidies	0.0022** (0.0010)	0.0016** (0.0010)	0.0004 (0.0000)
Number of parcels	−0.0002*** (0.0000)	−0.0002*** (0.0000)	−0.0001*** (0.0000)
Land transfer rate	−0.0479*** (0.0110)	−0.0416*** (0.0100)	−0.0219*** (0.0060)
Cons_	0.7060*** (0.0180)	0.7730*** (0.0160)	0.9090*** (0.0100)
N	3,088	3,088	3,088

***, **, and * are significant at the significance level of 1, 5, and 10%, respectively. Standard deviations are given in parentheses.

3.2 Analysis of the impact of farm size expansion on cost efficiency in sustainable rapeseed production

This section examines the influence of farm size expansion on cost efficiency in rapeseed production. As cost efficiency can be categorized into technical efficiency and allocative efficiency, the impact of farm size expansion on these two variables is also examined. Table 4 presents the empirical results, with Model 1 representing the effect of planting scale expansion on cost efficiency. Models 2 and 3 represent the effects on technical efficiency and allocative efficiency, respectively. The estimated coefficients of the variables in Models 1, 2, and 3 are −0.0266, −0.0241, and −0.0146, respectively, all significant at the 1% statistical level. These findings indicate that the scale of farm operation has a significant negative impact on the technical efficiency and cost efficiency of rapeseed growers. This suggests that expanding the operational scale does not necessarily lead to cost savings and is not conducive to improving technical efficiency, which aligns with the findings of Fan and Chan-Kang (2005) and Helfand and Levine (2004). Large-scale farmers incur higher management and supervision costs, and if the capacity for resource allocation cannot be correspondingly improved, cost efficiency will be reduced. Therefore, enhancing the cost efficiency of rapeseed production should focus on improving farmers' ability to allocate resources and adopt new technologies. These findings suggest that promoting sustainable production practices may require a shift away from large-scale farming and toward smaller-scale, more diversified farming systems. These findings have implications for food security, as improving cost efficiency and promoting sustainable production practices could make food more accessible and reduce the environmental impacts of agriculture.

In addition, we investigated the impact of control variables on rapeseed cost efficiency. The topographic features had a substantially negative impact on both technical and cost efficiency. This result indicates that geographical characteristics, such as hilly, mountainous, or alpine regions with uneven terrain and smaller-scale farmland, are not suitable for large-scale machinery operations and thus hinder rapeseed cost savings (Beckie and Warwick, 2010). Due to natural limitations, machinery that functions effectively in plains cannot be employed in hilly and mountainous areas, resulting in a significant decrease in machinery utilization rates (Cao et al., 2023). Notably, the distance to the closest farmers' market exhibited a significant inverse relationship with rapeseed production cost efficiency. This finding suggests that farmers located farther away from farmers' markets may incur higher costs associated with purchasing supplies, such as seeds, fertilizers, pesticides, transportation, and labor, leading to an overall increase in total costs. Conversely, the distance to the nearest agricultural extension institution showed a significant positive correlation with rapeseed production cost efficiency. This outcome can be attributed to the fact that agricultural extension centers at the county level and above possess stronger faculty and more effective skill transfer capabilities compared to those at the township level. This finding aligns with the notion that technical training, similar to education, exhibits a positive trend in terms of faculty quality and desired outcomes as the level of training increases (Ye et al., 2023).

The proportion of hired labor significantly negatively affects cost efficiency and technical efficiency. The possible explanation is that as urbanization accelerates, hiring labor becomes more expensive, leading to an increase in the total cost of rapeseed production, which does not contribute to improving cost efficiency (He et al., 2017). In addition, there is a substitution effect between the share of hired labor and technology adoption, meaning that a higher proportion of hired labor hinders improvements in technological efficiency (Afonso and Leite, 2010). In contrast, the estimated coefficient of rapeseed production subsidy is significantly positive at the 1% level, emphasizing the importance of policy factors in rapeseed production. This finding highlights the need to improve China's agricultural subsidy policy, diversify subsidy types, and adopt more flexible subsidy methods to enhance subsidy effectiveness (Guo et al., 2021; Zhang, 2022), which is consistent with the conclusions of Liu Q. et al., 2017 and Leng et al. (2021). On the other hand, the land transfer rate significantly negatively affects cost efficiency, technical efficiency, and allocation efficiency. One possible reason is the phenomenon of dispersed land transfer among rapeseed farmers, which can lead to more severe land fragmentation (Liang et al., 2020). This, in turn, increases the inputs of fertilizers and other production factors, potentially offsetting any potential improvements in cost efficiency. These findings suggest that sustainable production and food security require a balance between labor, technology, and land resources, which can be achieved through improved subsidy policies and land consolidation.

3.3 Sustainability-centric heterogeneity analysis

We also conduct heterogeneity analysis to examine how cost efficiency and its decomposition vary across farmers of different sizes, in diverse regions, and under varying terrain conditions. These results help us develop targeted strategies to enhance cost efficiency for farmers based on their specific circumstances.

3.3.1 Regional heterogeneity analysis

China's goal of becoming an agricultural powerhouse depends on narrowing regional agricultural productivity gaps. This will both stabilize the supply of key agricultural products and boost farmers' income (Gong, 2022). Resource endowment, economic development, and agricultural policies can significantly influence rural industries. These factors may cause regional disparities in how farm operation scale impacts the cost efficiency of rapeseed production across China's western, central, and eastern regions. Therefore, sustainable agricultural development must address these regional differences to improve rapeseed production efficiency. This is particularly important in China's central and western regions, which hold significant potential for increased rapeseed production efficiency and contribute to global agricultural modernization.

3.3.1.1 Regional heterogeneity of cost efficiency

The cost efficiency of rapeseed production in eastern China is inverted U-shaped with the expansion of farmers' operating scale (Table 5). It is optimal in the interval of 10 to 30 mu. Cost efficiency, technical efficiency, and allocation efficiency were also higher in the eastern region than in the central and western regions. These findings align with Liu Q. et al., 2017. This may be attributed to terrain conditions, economic development, local support policies, and the quality and skills of farmers in the eastern region (Jin et al., 2010). Technical and allocation efficiency also exhibit inverted U-shaped trends and are higher than in the central and western regions.

With scale expansion, the cost efficiency of rapeseed production in central China follows an inverted U-shaped trend and has the highest efficiency value in the interval of 10 to 30 mu. Cost efficiency, technical efficiency, and allocation efficiency were significantly higher in the central region than in the western region but lower than in the eastern region. This finding might be related to the fact that Hubei and Hunan in the central region are primary winter rapeseed producing areas and the local government emphasizes moderate-scale operation and sustainable rapeseed development (Zheng et al., 2020). Moreover, the central region's landscape is dominated by mountains and hills, with large undulating and scattered land parcels. The fragmentation of cropland is prominent, and cropland remediation lags behind other regions (Tang et al., 2023), affecting the improvement of rapeseed production cost-effectiveness.

The findings reveal that in Western China, rapeseed production's cost efficiency is lower than in the eastern and central regions, showing a downward trend with an optimal level below 10 mu. This disparity can be attributed to several factors, including differences in topography, geomorphology, infrastructure, the completeness of the factor market, and existing agricultural technology. Additionally, small farmers in the western region tend to make more rational factor inputs in small-scale cultivation or over-invest their own labor to replace other production factors, aiming to maximize output per unit of land (Li et al., 2010). However, this approach results in optimal cost efficiency.

These results show that the cost efficiency of rapeseed production in China varies across regions and exhibits an inverted U-shaped relationship with the expansion of farmers' operating scale. The eastern region has the highest cost, technical, and allocation efficiency, followed by the central region and the western region. These findings align with previous studies and can be attributed to factors such as terrain conditions, economic development, local support policies, and the quality and skills of farmers. From a sustainable production perspective, improving cost efficiency and resource allocation in rapeseed production can contribute to reducing environmental

TABLE 5 Efficiency and decomposition of rapeseed production in different regions.

Regions	Variables	<10 mu	10–30 mu	30–50 mu	50–100 mu	100–200 mu	>200 mu
Eastern region	Cost efficiency	0.722	0.788	0.758	0.717	0.687	0.582
	Technical efficiency	0.784	0.839	0.816	0.781	0.758	0.663
	Allocation efficiency	0.912	0.937	0.928	0.912	0.902	0.845
Central region	Cost efficiency	0.698	0.713	0.668	0.610	0.567	0.498
	Technical efficiency	0.764	0.775	0.739	0.685	0.694	0.587
	Allocation efficiency	0.901	0.905	0.891	0.859	0.842	0.805
Western region	Cost efficiency	0.663	0.631	0.513	0.515	0.508	0.486
	Technical efficiency	0.736	0.710	0.604	0.607	0.601	0.573
	Allocation efficiency	0.891	0.88	0.821	0.825	0.823	0.780

impacts and enhancing long-term food security. Moreover, promoting sustainable production practices, such as adopting integrated pest management and optimized fertilizer application, can help maintain high yields while minimizing costs and environmental degradation.

3.3.1.2 Regional heterogeneity in the impact of farm size expansion on cost efficiency

China is known for its large geographical area with significant regional variations. To further examine these differences, we analyze the regional impact of farm size expansion on the cost efficiency of farm households, as shown in Table 6. Models 1, 2, and 3 present the estimation results for the eastern, central, and western regions, respectively.

Several conclusions can be drawn from these findings. First, the scale of farm operations has a significant negative impact on all three types of efficiency of rapeseed growers in the eastern region. However, comparing the regression coefficients reveals that the negative effect in the central region is smaller than that in the eastern region, and that in the eastern region is smaller than that in the western region. This finding is related to the support policies for rapeseed production in the central region, particularly in Hubei and Hunan provinces, which are two major rapeseed-producing provinces. The support provided by the relevant governments and research institutes in these provinces for rapeseed research, development, and production is substantial. In addition, the topographic characteristics of farmland had a significant positive effect on all three efficiencies of rapeseed growers in the eastern region. This suggests that the plain topographic conditions in the eastern region are favorable for promoting agricultural machinery services, which in turn improves cost efficiency (Liu Q. et al., 2017). However, the significance of this effect in the central and western regions is less pronounced than in the eastern region.

Second, the proportion of hired labor significantly negatively affects cost and technical efficiency in the eastern region. This negative effect is smaller in the eastern region than in the central region, possibly due to the quality of hired labor. The eastern region has more systematic and effective training programs for professional farmers.

Third, the estimated coefficient of rapeseed production subsidy is significantly positive at the 1% level in the eastern region, but not significant for the central and western regions. There is even a negative effect for the western region. This finding suggests a usability problem with the subsidy policy. Specifically, implementing subsidy policies in different regions does not necessarily have a positive effect on rapeseed production (Zhang et al., 2022).

These findings indicate regional disparities in the impact of farm size expansion on the cost efficiency of rapeseed growers in China. The negative effect of farm size on efficiency is more pronounced in the eastern region than in the central and western regions. This finding is related to the support policies for rapeseed production in the central region and the topographic characteristics of farmland in the eastern region. These results have implications for sustainable food production, as they suggest that farm size is not the only factor that affects the efficiency of agricultural production. Other factors, such as government support and topographic conditions, also play an important role.

3.3.2 Analysis of terrain heterogeneity

China is characterized by a diverse topography, encompassing plains, hills, mountains, and plateaus. Consequently, the divergent terrain conditions exert a profound influence on the efficiency of rapeseed production. Therefore, investigating its heterogeneity presents a valuable opportunity to inform and guide the sustainable development of the rapeseed industry.

3.3.2.1 Terrain heterogeneity of cost efficiency

Table 7 reveals that the cost efficiency of rapeseed production in China's plain areas exhibits an inverted U-shaped pattern as farmers' operation scale expands. The overall efficiency value is higher than in non-plain areas and is optimal in the two intervals of 10–30 mu and

TABLE 6 Results of regional heterogeneity in the effect of farm size on cost efficiency.

Variables	Model 1	Model 2	Model 3
	Cost efficiency	Cost efficiency	Cost efficiency
Farm size	−0.0177*** (0.0050)	−0.0291*** (0.0040)	−0.3810*** (0.0060)
Gender	0.0158 (0.0160)	−0.0215 (0.0160)	−0.0153 (0.0150)
Age	0.0000 (0.0010)	−0.0000 (0.0020)	−0.0002 (0.0000)
Education	−0.0004 (0.0020)	−0.0003 (0.0020)	0.0003 (0.0020)
Health status	0.0133 (0.0100)	0.0098 (0.0080)	0.0037 (0.0080)
Distance to markets	−0.0038* (0.0020)	−0.0059*** (0.0020)	−0.0063*** (0.0020)
Distance to agricultural institutions	−0.0001 (0.0010)	−0.0072*** (0.0010)	0.0051*** (0.0020)
Hired worker weight	−0.0619** (0.0290)	−0.0846*** (0.0190)	0.0239 (0.0031)
Topography	0.0515*** (0.0110)	−0.0091 (0.0090)	0.0403*** (0.0160)
Subsidies	0.0080*** (0.0020)	0.00213 (0.0010)	−0.0016 (0.0020)
Number of parcels	−0.0002 (0.000)	−0.0002*** (0.0000)	−0.0007** (0.0000)
Land transfer rate	0.0277 (0.0280)	−0.0872*** (0.0170)	−0.0128 (0.0180)
Cons_	0.6700*** (0.0590)	0.7430*** (0.0270)	0.7490*** (0.0350)
N	660	1,430	998

***, **, and * are significant at the significance level of 1, 5, and 10%, respectively. Standard deviations are given in parentheses.

TABLE 7 Cost efficiency and decomposition in different terrain.

Regions	Variables	<10 mu	10–30 mu	30–50 mu	50–100 mu	100–200 mu	>200 mu
Plains region	Cost efficiency	0.714	0.729	0.696	0.730	0.653	0.506
	Technical efficiency	0.777	0.788	0.762	0.790	0.726	0.596
	Allocation efficiency	0.906	0.910	0.902	0.916	0.885	0.809
Non-plain region	Cost efficiency	0.720	0.691	0.606	0.523	0.530	0.412
	Technical efficiency	0.782	0.758	0.685	0.609	0.617	0.511
	Allocation efficiency	0.909	0.896	0.864	0.821	0.816	0.761

TABLE 8 Results on terrain heterogeneity in the effect of farm size on cost efficiency.

Variables	Model 1	Model 2
	Cost efficiency	Cost efficiency
Farm size	−0.0105** (0.0050)	−0.0236*** (0.0040)
Gender	0.0084 (0.0150)	−0.0234** (0.0120)
Age	0.0000 (0.0000)	−0.0002 (0.0000)
Education	0.0034** (0.0020)	−0.0017 (0.0010)
Health status	0.0222*** (0.0080)	0.0041 (0.0060)
Distance to markets	0.0008 (0.0020)	−0.0118*** (0.0020)
Distance to agricultural institutions	0.0016 (0.0010)	0.0078*** (0.0010)
Hired worker weight	−0.1580*** (0.0230)	0.0086 (0.0180)
Subsidies	0.0034** (0.0010)	0.0008 (0.0010)
Number of parcels	−0.0009*** (0.0000)	−0.0001** (0.0000)
Land transfer rate	−0.0309 (0.0190)	−0.0562*** (0.0140)
Cons_	0.6360*** (0.0290)	0.7770*** (0.0280)
N	998	2090

***, **, and * are significant at the significance level of 1, 5, and 10%, respectively. Standard deviations are given in parentheses.

50–100 mu. Notably, there is no significant difference between the efficiency values of plain and non-plain areas in the interval of less than 10 mu. However, beyond the 200 mu interval, the efficiency values of plain areas significantly surpass those of non-plain areas. These findings highlight the influence of topography, landscape, and infrastructure conditions and suggest that natural factors continue to exert a significant impact on crop production. Small-scale farmers in the plains need to capitalize on their efficiency advantages when operating on a small scale. As the scale increases, more farmers in the plains region are adopting mechanization, facilitating continuous and specialized production and thereby realizing the external scale economies of specialized agglomeration (Zhang and Luo, 2020). Nonetheless, there is substantial room for improvement in cost efficiency for both plains and non-plains scale households. Small-scale farmers in China's plain areas have the potential to contribute to sustainable agriculture due to the higher cost efficiency of rapeseed production in these regions. These findings indicate that small-scale farmers can play a significant role in sustainable food production. By leveraging their efficiency advantages, small-scale farmers can increase food production, improve food security, and minimize environmental impacts. Mechanization and specialized production in the plains region can further enhance cost efficiency and support sustainable food production. This shift toward small-scale, efficient farming practices can contribute to the long-term sustainability of China's agricultural sector and ensure food security for future generations.

3.3.2.2 Regional heterogeneity in the impact of farm size expansion on cost efficiency

In this section, we conduct a more detailed analysis of the topographic differences in the impact of farm size expansion on farmers' cost efficiency. The results of this analysis are presented in Table 8. Models 1 and 2 present the estimation results of farm size expansion on cost efficiency in the plains and non-plains regions, respectively, for farmers.

The findings reveal several key insights. First, farm size significantly influences the cost efficiency and technical efficiency of rapeseed farmers in the plains. However, the negative effect is less pronounced compared to non-plain areas, as indicated by the regression coefficients. This suggests that the more favorable terrain conditions in the plains enhance the efficiency and adoption of mechanization in rapeseed production, mitigating the negative impact on cost efficiency (Yang and Li, 2022; Cao et al., 2023). Second, the number of individual plots has a substantial negative influence on cost efficiency in the plains of China. The regression coefficients reveal that this influence is more significant and detrimental than in non-plain areas. This finding suggests that when land fragmentation occurs in the plains, the cost of labor and machinery operations rises substantially (Wang et al., 2020), leading to a more severe adverse impact.

Third, the level of education among agricultural decision-makers in the plains demonstrated a positive correlation with both cost efficiency and technical efficiency in rapeseed production. However, the relationship between education level and efficiency in the non-plains region was negative. This contrast may indicate that farmers in the plains can better integrate their acquired knowledge with their existing knowledge system and apply it to agricultural production effectively during more comprehensive agrotechnical training (Ruzzante et al., 2021). Fourth, the health status of agricultural decision-makers in the plains significantly affects all three categories of efficiency. Compared with allocative efficiency, technical efficiency is more substantially influenced by health status, as indicated by the regression coefficients.

Fifth, all three types of efficiency in the plains are significantly and negatively impacted by the proportion of hired labor. The negative effects of the proportion of hired labor in the plains are greater than those in the non-plains, as evidenced by the regression coefficients. Sixth, the estimated coefficient of rapeseed production subsidy is significantly positive at the 5% level. This finding suggests that the plains' subsidy policy positively influences cost and technical efficiency. It also indicates that the plains' subsidy policy may have adopted a more diversified and flexible approach to enhance subsidy effectiveness.

In addition, in non-plain areas, field limitations restrict the use of large and medium-sized machinery for rapeseed planting, plant protection, and harvesting. Small machinery, while usable, suffers from lower operating efficiency, thereby increasing operational costs. This situation discourages farmers from adopting mechanization, ultimately hindering efforts to improve production efficiency in rapeseed expansion (Tang et al., 2023).

These findings show that farm size expansion has a significant negative impact on the cost efficiency of rapeseed farmers in China, especially in non-plain areas. The number of individual plots, the level of education of agricultural decision-makers, and the health status of agricultural decision-makers also have significant effects on cost efficiency. These findings suggest that policies aimed at promoting sustainable agriculture and food security should consider the topographic differences in the impact of farm size expansion and other factors on farmers' cost efficiency.

3.4 Further analyses on plot-level data

Solely relying on land-use right transfers to expand farm size can have negative consequences. Without measures to address land fragmentation and ensure continuous land use, this approach may lead to decreased production efficiency and weaken the economic benefits of larger farms (Guo et al., 2019; Gao and shi, 2019). Therefore, to further explore the moderating role of plot size in the effect of farmers' scale of operation on the cost efficiency of rapeseed production, this section introduces the interaction term of plots for further analysis. Models 1, 2, and 3 are regression results based on cost, technical, and allocation efficiency, respectively.

Table 9 shows that plot size plays a negative moderating role in the effect of farm size on the cost efficiency of rapeseed production. In other words, the negative effect of farm size on cost efficiency decreases when the plot size is larger. Several reasons may explain these results. First, when land transfer results in an increase in rapeseed plot size and a decrease in land fragmentation, it encourages farmers to reduce inputs such as fertilizers and labor in rapeseed production (Liang et al., 2020), which effectively improves the cost efficiency of rapeseed production. Second, plot size is related to the fine fragmentation of arable land, which presents several challenges. On the one hand, the increase in ridge and furrow areas makes it difficult to operate or popularize large agricultural machinery. On the other hand, fine fragmentation of cultivated land hampers the effective control of large-scale pests and

TABLE 9 Effect of plot size on efficiency.

Variables	Model 1	Model 2	Model 3
	Cost efficiency	Technical efficiency	Allocation efficiency
Farm size	−0.0272*** (0.0030)	−0.0326*** (0.0070)	0.0011 (0.0070)
Farm size×Plot size	0.0039** (0.0020)	0.0032* (0.0020)	0.0009 (0.0010)
Gender	−0.0133 (0.0090)	−0.0124 (0.0080)	−0.0318 (0.0190)
Age	−0.0001 (0.0000)	−0.0001 (0.0000)	−0.0001 (0.0000)
Education	0.0011 (0.0010)	0.0010 (0.0010)	0.0006 (0.0010)
Health status	0.0114** (0.0050)	0.0103** (0.0040)	0.0066** (0.0030)
Topography	0.0339*** (0.0060)	0.0283*** (0.0050)	0.0128*** (0.0030)
Distance to markets	−0.0076*** (0.0010)	−0.0060*** (0.0010)	−0.0022*** (0.0010)
Distance to agricultural institutions	0.0061*** (0.0010)	0.0049*** (0.0010)	0.0020*** (0.0010)
Hired worker weight	−0.0568*** (0.0150)	−0.0439*** (0.0130)	−0.0105 (0.0080)
Subsidies	0.0022** (0.0010)	0.0017** (0.0010)	0.0005 (0.0000)
Number of parcels	−0.0002*** (0.0000)	−0.0002*** (0.0000)	−0.0001*** (0.0000)
Cons_	0.7190*** (0.0190)	0.7850*** (0.0170)	0.9130*** (0.0100)
N	3,088	3,088	3,088

***, **, and * are significant at the significance level of 1, 5, and 10%, respectively. Standard deviations are given in parentheses.

diseases (Petit et al., 2020; Kennedy and Huseth, 2022). Third, in the transfer market, either forming a contiguous plot with the original land location or transferring to a larger plot can improve technical efficiency, thus reducing the average cost per product unit. This suggests the presence of economies of scale at the plot level. However, it's worth noting that while the simultaneous expansion of plot size and farmers' scale of operation is beneficial to cost efficiency and technical efficiency, its effect on allocative efficiency is not significant.

These findings have implications for sustainable food production and food security. Firstly, the negative moderating role of plot size in the effect of farm size on cost efficiency suggests that land consolidation policies that encourage the formation of larger contiguous plots can improve the cost-effectiveness of rapeseed production. This, in turn, can make rapeseed production more competitive and contribute to increased food production. Secondly, the economies of scale at the plot level suggest that larger plots can be more efficient in using inputs such as fertilizers and labor, which can reduce the environmental impact of rapeseed production and promote sustainable agriculture. Thirdly, the positive effect of plot size on technical efficiency implies that larger plots can adopt more advanced technologies and practices, which can increase productivity and contribute to food security. Fourth, policies should actively promote land consolidation to reduce fragmentation further. Larger plots enable the use of mechanized application techniques and equipment, which improves fertilizer efficiency, reduces production costs (Zhang and Luo, 2020), and contributes to greater productivity.

4 Conclusion and policy recommendations

4.1 Conclusion

This research investigates the economic efficiency of rapeseed production in China from 2018 to 2021, emphasizing the role of cost efficiency in promoting sustainable agriculture and securing food supplies. Through stochastic frontier analysis (SFA), we decompose cost efficiency into technical and allocative efficiency, analyzing the impact of operation scale and plot size on these efficiencies. Our study also considers regional and terrain-related differences in efficiency outcomes. The following points summarize our findings and their implications for sustainable food production and food security:

Firstly, our analysis revealed that rapeseed production in China exhibits room for improvement in cost efficiency. With technical efficiency at 0.740, allocative efficiency at 0.889, and overall cost efficiency at 0.670, there is a significant gap from the optimal cost frontier, indicating a potential 33% efficiency gain.

Second, the study shows an inverted U-shaped relationship between farm operation scale and cost efficiency, with differences across regions and terrains. This suggests that there is an ideal scale of operation for maximizing cost efficiency, beyond which efficiency declines. The variability in efficiency due to personal characteristics, resource endowment, and production traits highlights the complexity of achieving optimal cost efficiency.

Thirdly, in China's eastern regions, cost efficiency peaks within a 10–30 mu operation scale before declining. This regional analysis shows that cost, technical, and allocative efficiencies are higher in the east compared to the central and western regions. The impact of farm size on efficiency varies by region, indicating that regional strategies are needed to optimize rapeseed production scales.

Fourth, our findings indicate a decline in technical and allocative efficiencies with the expansion of rapeseed production in non-plain areas, particularly notable in operations of less than 10 mu. The negative impact of larger farm sizes on efficiency was less pronounced in plain areas, suggesting that terrain plays a significant role in determining the optimal scale for rapeseed production.

Fifth, plot size was found to moderate the negative impact of operation scale on cost efficiency. Larger plot sizes can mitigate the adverse effects of increasing farm size on cost efficiency, pointing to the benefits of consolidating land for rapeseed cultivation. However, this does not significantly affect allocative efficiency.

4.2 Policy recommendations

Based on the findings from our research, we suggest a set of policy measures aimed at improving the economic sustainability of the rapeseed industry and thereby supporting sustainable food production and food security:

Firstly, there is a clear need to focus on enhancing both cost and allocation efficiency within the rapeseed sector to strengthen its global competitiveness. This involves, on one hand, reforming the factor markets to ensure equal financial opportunities for farmers regardless of their operation scale. Financial market reforms should aim at providing equitable loan access to support both small and large-scale rapeseed producers. On the other hand, enhancing scientific research, technological innovation, and the dissemination of technology in rapeseed production is essential. Efforts should be directed toward increasing the application of scientific and technological advancements in rapeseed cultivation, including the development of high-quality seed varieties, soil and fertilizer management improvements, and machinery advancements. Furthermore, economic studies on the rapeseed industry should be encouraged to identify optimal scales of operation and management practices that can lead to cost reductions and efficiency improvements.

Secondly, while promoting land transfers to realize economies of scale at the plot level, it is critical for local government entities to refine the agricultural land transfer system. This system should encourage the consolidation of fragmented land parcels and support continuous land transfers, moving away from the historically decentralized land transfer practices. Government agencies should guide the centralized transfer of agricultural land, leveraging policy support, land rights clarification, and service optimization to facilitate the aggregation of arable land. This strategy aims to diminish the excessive fragmentation of arable land, enhancing plot-level economies of scale.

Thirdly, provincial and municipal authorities are advised to develop rapeseed cultivation strategies that are tailored to the specific zonal characteristics, promoting a coordinated and sustainable regional development approach. Targeted policies should consider the unique natural resources, topographical conditions, farmland infrastructure, and familial resources of each region. For instance, in the eastern plains, where natural conditions and farmland infrastructure are superior, implementing crop rotations between rice and rapeseed on a scale of 10–30 mu could achieve significant economies of scale. Furthermore, encouraging a culture of knowledge and experience exchange among different rapeseed producing areas can create a supportive network, enhancing regional development synergistically.

These recommendations aim to guide policy formulation toward enhancing the rapeseed industry's efficiency, contributing to the broader objectives of sustainable agricultural practices and food security. By addressing financial accessibility, technological advancement, land management practices, and regional development strategies, these policies can support the rapeseed industry's evolution into a more economically sustainable and ecologically responsible sector.

4.3 Research limitations and prospects

While our study contributes new evidence for sustainable agricultural development in China, it has limitations. First, data availability restricts our analysis to the year 2021; ongoing data collection will enable extended research. Second, we focused on cost-efficiency as a metric for agricultural sustainability. Future research could broaden this scope by examining the impact of land consolidation on green 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 authors.

Author contributions

QZ: Formal analysis, Writing – review & editing, Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft. FY: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Data curation, Investigation, Software. AR: Writing – review & editing, Formal analysis. ZF: Data curation, Funding acquisition, Project administration, Writing – review & editing. YL: Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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