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Sustainable potato farming in Shandong Province, China: a comprehensive analysis of organic fertilizer applications

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Introduction: The potato holds the distinction of being the world's largest non-cereal food crop and ensuring its sustainable production is imperative for global food security. Notably, China leads in both the planting area and output of potatoes globally, cementing its crucial role in the nation's agricultural economy. A scientific assessment of the effectiveness of organic fertilizers on potato cultivation can significantly contribute to the promotion of sustainable agriculture.

Methods: This study utilizes a Propensity Score Matching (PSM) model and introduces a novel cost-efficiency approach to analyze and evaluate the production efficiency and economic impact of organic fertilizer application among 546 potato growers in Shandong.

Results: The research findings reveal the following: Firstly, compared to the control group without organic fertilizer application, it is evident that the use of organic fertilizers enhances production technology efficiency, labor productivity, land productivity, and net profit per unit by 3.6%, 1588.47 kg/person, 16346.77 kg/ha, and 16135.32 yuan/ha, respectively. Secondly, an examination of cost efficiency among growers with different production scales indicates that those with a planting scale of 0.667-1.333 hectares demonstrate relatively high production efficiency across multiple factors. Additionally, there is an observable inverted U-shaped trend in the relationship between planting scale and production efficiency. Thirdly, the continuous application of organic fertilizers proves advantageous in mitigating inefficiencies in investment techniques, leading to cost savings and efficiency improvements in potato cultivation.

Discussion: Consequently, it is recommended that the government and relevant departments enhance technical support, elevate professional training programs, and optimize the allocation of input factors. These measures aim to encourage farmers to adopt organic fertilizers, thereby promoting sustainable agricultural practices.

KEYWORDS

economic effect, organic fertilizer application, PSM model, cost efficiency model, potato growers

1 Introduction

The continuous progression of green agricultural technology plays a crucial role in achieving China's dual objectives of reducing the quantity and enhancing the efficiency of chemical inputs (Xu et al., 2014; Yi et al., 2021), while effectively mitigating non-point source pollution in agriculture (Adnan et al., 2017a; Luthra et al., 2022). As per statistical findings from the Ministry of Agriculture and Rural Affairs, the policy initiated in 2015 to decrease chemical fertilizer and pesticide quantities while improving efficiency resulted in a 13.8% decrease in China's application of agricultural chemical fertilizers (51.91 million tons, actual purity) and a 16.8% reduction in pesticide use (248,000 tons) in 2021 compared to 2015 (Li and Shen, 2021; Fan P. et al., 2023). Despite this apparent decline in the usage of chemical products, persistent issues related to non-point source pollution and concerns about food quality and safety due to long-term excessive application continue to significantly impact both product quality and sustainable agricultural development (Ma et al., 2018; Wang et al., 2019). The No. 1 Central Document issued in 2023 emphasizes the urgency of accelerating the adoption and implementation of technologies that facilitate agricultural product quantity reduction and efficiency improvement, thereby promoting the green development of agriculture (Chadwick et al., 2015; Zhang et al., 2020). Subsequently, an increasing number of scholars have provided evidence supporting the viabilities of green agricultural technology such as green fertilizers and green control measures to foster sustainable development in agriculture (Asfaw et al., 2016; Ikram et al., 2021; Moli et al., 2021).

Seemingly, the existing literature studies have already demonstrated the efficacy of employing various eco-friendly technologies in agricultural production to mitigate non-point source pollution (Naher et al., 2021; Movahedi et al., 2023). These technologies include the substitution of chemical fertilizers with organic fertilizers, soil improvement measures, cover crops, and better straw and residue amendments. The implementation of these green agricultural practices not only enhances the quality of agricultural products but also significantly improves the ecological environment in production areas in the long run (Mao et al., 2005; Dong et al., 2022). For example, a study of green fertilizer application in Maize production in sub-Saharan Africa, (Sileshi et al., 2009) indicated that green manure application indicated a significant increase in yield response. Egodawatta et al. (2012), Baweja et al. (2020), and Krasilnikov et al. (2022) advocated that green fertilizers such as manure are derived from natural sources the application of these eventually foster better soil organic matter, safeguard ecosystems and maintain soil quality. In a study of apple growers in China Wang et al. (2018) found that organic fertilizer significantly lowered the cost and maintain profitability. Epule (2019) outlined critical prospects of green technologies such as organic fertilizer in maintaining a safer food supply for the community. Therefore, it can be concluded that the promotion of green agricultural technology holds significant importance in ensuring both production attributes such as a better and a sustainable environment, fostering sustainable agricultural development. The progress of green agricultural technology faces a notable challenge in terms of limited adoption among smallholder farmers (Bukchin and Kerret, 2018; Adnan et al., 2019b; Mao et al., 2021), indicating a substantial path ahead to comprehend these sustainable agricultural practices (Adnan et al., 2018, 2019a; Tanko et al., 2023). Challenges also persist in achieving widespread adoption among marginal farmers, attributed to factors such as high labor costs, time requirements, investment expenditures, and equipment demands associated with production processes (Chen et al., 2018; Wang X. et al., 2021).

Currently, the application quantity of agricultural chemical fertilizers significantly exceeds the optimal amount required for agricultural production. However, due to the influence of the law of diminishing marginal returns, excessive use of chemical fertilizers impedes improvements in agricultural productivity (Harraq et al., 2022). Organic fertilizer application, as a prominent technology in sustainable agriculture, not only provides substantial economic benefits to farmers but also aligns with environmentally-friendly farming practices for the enhancement of the ecological environment (Daadi and Latacz-Lohmann, 2021b). The issue of food security consistently poses a significant constraint on the economic development of our nation. Given China's substantial population and ever-decreasing trends of agricultural land, achieving substantial increases in both total output and planting area for traditional food crops within a short timeframe is indeed challenging (Yi et al., 2021). However, potato cultivation in China currently holds the top position globally in terms of both planting area and production volume, playing a significant role in the agricultural economy (Yin et al., 2023). According to statistics, China's potato planting area accounts for approximately one-fourth of the global total. Moreover, an annual consumption of at least 655,000 tons of chemical fertilizers is dedicated solely to potato cultivation (Shi M. et al., 2023); however, the efficiency of fertilizer utilization remains suboptimal (Jiang L. et al., 2023; Yang et al., 2023). The application of excessive fertilization practices can result in a decline in potato yield, compromised quality, and adverse impacts on economic profitability (Zhang F. et al., 2023a). Therefore, judicious control of chemical fertilizer dosage and optimization of fertilization methods have emerged as crucial strategies for enhancing potato production. In existing agricultural settings, reducing chemical fertilizer usage while incorporating organic fertilizers represents a crucial strategy for enhancing crop quality and efficiency (Shi X. et al., 2023; Xu et al., 2023).

However, existing studies primarily focus on organic fertilizer application on potato agronomic traits, yield, quality, and related factors (Fan H. et al., 2023; Shi X. et al., 2023). Notably, factors influencing the application of organic fertilizers to potatoes encompass various aspects such as new variety considerations, farmer endowment, technical environment characteristics, and so on (Adnan et al., 2019a). Despite the growing interest in the influencing factors of farmers' behavior regarding organic fertilizer application in existing literature (Amfo and Ali, 2021; Xie et al., 2021; Ochieng et al., 2022; Mwakidoshi et al., 2023), there remains a dearth of documents examining the impact of potato growers' utilization of organic fertilizers from the perspectives of production efficiency and planting benefits. The current body of research predominantly focuses on assessing the efficiency of potato production (Priegnitz et al., 2019; Imani et al., 2021; Naghdi et al., 2022), often overlooking the crucial role played by the application of organic fertilizers. By incorporating a dedicated emphasis on the dynamic interaction between organic fertilizer and production efficiency, scholars can uncover nuanced insights into the sustainability and environmental impact of potato cultivation. This integration is imperative, particularly in light of the escalating emphasis on sustainable agricultural practices and the imperative to minimize the environmental footprint of farming activities. While extant research touches upon various determinants of adoption [such as Imani et al. (2021), Andati et al. (2022), and Nazziwa-Nviiri et al. (2017)], the connection to operational income remains insufficiently explored. Understanding how the application of organic fertilizers influences the socio-environmental and economic aspects of potato production is pivotal for both farmers and policymakers. This research aims to provide valuable information regarding the economic viability of adopting organic fertilizers, with the potential to influence agricultural practices and policies. However, the Planting scale stands out as a pivotal factor in agricultural operations, and its impact on efficiency should also be explored sufficiently. Therefore, we also explored how different planting scales influence production efficiency through organic fertilizer application to fill a notable research gap. Through the implementation of innovative cost-efficiency decomposition methods, the study tends to provide a though investigation, offering insights into the cost-effectiveness of diverse planting scales and guiding farmers in optimizing their operations. This avenue of investigation aligns with academic rigor and has the potential to contribute meaningfully to both theoretical understanding and practical applications in the field of organic fertilizer application. More specifically, the study seeks to answer the following inquiries: (i) What are the economic implications of organic fertilizer application for potato growers? (ii) Can it enhance potato production efficiency? (iii) Can it mitigate the adverse effects of inefficient technology investment on cost efficiency? The answers to these questions can contribute significantly toward facilitating widespread implementation and effective promotion of green agricultural practices such as organic fertilizers.

2 Literature review

The advancement of agriculture toward high-quality development necessitates a comprehensive improvement in productivity through the application of advanced technologies, equipment, and modern management methods (Wu et al., 2011; Adnan et al., 2017b). This enhancement is crucial for promoting increased agricultural productivity. The investment in various factors of agricultural production, including labor, land, capital, and technology, plays a fundamental role in this development (Daadi and Latacz-Lohmann, 2021a). Some scholars propose that stimulating investments in organic fertilizers can effectively enhance soil quality and land productivity, subsequently leading to an overall improvement in labor productivity (Mueller et al., 2019; Zhang L. et al., 2023). This approach aligns with the emerging trend of intensive cultivation in China's agriculture, adapting to limited land resources and striving to significantly improve both land and labor productivity over its long history.

In accordance with the theories of factor endowment and comparative advantage, the scarcity of production resources and the resource endowment of producers exert significant influence on the decision-making of farmers regarding the application of organic fertilizers (Amoroso et al., 2011). Acting as rational economic agents, farmers often base their decisions on the use of organic fertilizers on their resource endowment and comparative cost advantages (Li X. et al., 2021; Chen Z. et al., 2022). This decision-making approach facilitates the optimization and allocation of labor, capital, and other production factors, thereby contributing to the further enhancement of potato production efficiency. Therefore, the present study posits the hypothesis one as:

> *H1*: The application of organic fertilizer contributes to the enhancement of labor productivity and land productivity in potato production.

According to the theory of technical efficiency (Färe and Knox Lovell, 1978), when viewed from an investment perspective, the substitution of chemical fertilizers with organic fertilizers, while maintaining constant output scale and market prices, is anticipated to result in a reduction in the cost of organic fertilizer investment relative to chemical fertilizers at the same output level (Ali et al., 2020; Lampach et al., 2021). This transition is expected to bring about advancements in potato production technology efficiency. Furthermore, the strategic application of organic fertilizers holds the potential to mitigate the prospective increase in production costs that may arise from inefficient cost efficiency in agricultural production (Tzouvelekas et al., 2001; Madau, 2007). This implies that adopting organic fertilizers could lead to an enhanced level of productivity among growers. While acknowledging potential variations in technical proficiency levels among potato farmers, especially considering a fixed investment in other production factors, the judicious utilization of organic fertilizers is proposed to play a crucial role in narrowing the gap between actual yield and maximum potential yield (Blanchard et al., 2013; Li C. et al., 2021). This, in turn, is anticipated to contribute significantly to the enhancement of production efficiency (Salam et al., 2021). In light of these considerations, the present study formulates the following hypothesis:

> *H2*: The application of organic fertilizer contributes to the enhancement of technical efficiency in potato production.

Historically, traditional agriculture has been characterized by a predominant emphasis on optimizing agricultural production efficiency to achieve maximal yields (Holden, 2018; Jain et al., 2020). In contrast, the contemporary landscape of modern agriculture is undergoing a paradigm shift, placing primary importance on elevating farmers' income (Macharia et al., 2016; Triyono et al., 2023). This transformative shift is realized through the active promotion of green agricultural technologies and a committed effort to enhance the overall quality of agricultural products (Li Y. et al., 2021; Qi et al., 2021). An evaluation from the cost–benefit perspective reveals that green agricultural technologies while entailing higher initial costs, promise substantial returns over the long term (Li Y. et al., 2021).

In the context of potato cultivation, the adoption of organic fertilizers emerges as a pivotal practice that frequently leads to noteworthy enhancements in both product quality and output for farmers (Zenbaba, 2021). This dual improvement significantly contributes to an augmented income for agricultural practitioners. This perspective finds support in the work of Zhang L. et al. (2023), who demonstrate that the application of organic fertilizers has the potential to yield a sales income growth rate for agricultural products surpassing the associated costs. This outcome culminates in a definitive enhancement in overall profitability for farmers. The continual refinement and strategic allocation of production factors, coupled with advancements in cost efficiency (Takahashi et al., 2020; Ma et al., 2022), play indispensable roles in fostering a progressive increase in marginal yield (Ogada et al., 2014). Consequently, this positively influences crop productivity per unit area, thereby providing tangible benefits to farmers in terms of planting profitability. In light of these intricate dynamics, the present study posits the following hypothesis:

> *H3*: The application of organic fertilizer can enhance the unit output value and unit net profit in potato production.

Existing literature such as Adnan et al. (2018, 2019a) and Takahashi et al. (2020) highlight a complex interplay of factors shaping farmers' decisions to expand their planting scale and the consequent implications for the cost efficiency of organic fertilizer application. Moreover, some researchers highlight that, as farmers navigate the dynamic landscape of scale expansion, the initial positive correlation between increasing returns to scale and reduced unit area production cost sets the stage for an intriguing inquiry into the nuanced factors influencing agricultural decision-making (Li J. et al., 2020; Mao et al., 2021). According to Li et al. (2023), beyond the theoretical framework of economies of scale lies a critical juncture marked by a specific threshold in planting scale and the corresponding rise in the number of operated parcels. The intricate relationship between scale expansion, labor availability, and the diminishing marginal effect resulting from reduced production costs signifies a pivotal transition from a phase of cost-efficient scale expansion to a potential era of diseconomies of scale. This transition reflects the complexities inherent in optimizing production efficiency as factors of production are strategically invested (Avane et al., 2022; Chen Y. et al., 2022).

Upon the implementation of organic fertilizer, a consequential decline in cost efficiency emerges, gaining prominence amidst the continuous expansion of farmers' planting operations. This decline, notably pronounced in the context of scaling agricultural activities, suggests a shifting dynamic in the efficiency of organic fertilizer application. The emerging trend mirrors an inverted U-shaped trajectory, characterized by an initial ascent in efficiency followed by a subsequent descent. This distinctive pattern prompts an exploration of the underlying factors contributing to the observed fluctuations in efficiency during the expansion of the planting scale. In light of these multifaceted dynamics, we posit the following hypothesis to encapsulate the intricate relationship between planting scale, organic fertilizer application, and cost efficiency:

> *H4*: The cost efficiency of organic fertilizer application exhibits an inverted U-shaped trend with the expansion of planting scale.

Based on the aforementioned arguments, we have derived a theoretical framework for analyzing the economic impact of organic fertilizer application, as depicted in Figure 1.

3 Materials and methods

3.1 Data sources

In 1937, Austrian scholar Von Bertalanffy (1950) defined a system as a set of interrelated elements, thus formally putting forward the concept of general system theory. Systems theory provides a comprehensive framework for quantifying the elements of a system as a whole and explains its structure, function, behavior, and dynamics (Rice, 2013). The theory's core idea is to emphasize any particular system's overall concept (Drack and Apfalter, 2007). System thinking has transformed people from a systematic conception of looking at isolated and scattered and a disciplinary notion of looking at connected, organic, and holistic things. It is a new paradigm of scientific thinking, each element in the system does not exist in isolation, and each part plays a specific role in the system (Biazzo, 2002). The external conditions of the system refer to the environment, which denotes the collection of factors outside the system that affect the system itself. The external environmental element and the system are inseparable and interconnected (Järvilehto, 2009; Virapongse et al., 2016).

The data for this paper were gathered through an on-site questionnaire survey conducted in the primary potato-producing region of Tengzhou City, Shandong, between March and April 2023. Notably, we employed a multistage random sampling approach in our study. Initially, Shandong Province was purposefully selected due to its status as one of the major provinces facilitating modern potato processing industries (Wang Z. et al., 2023). Similarly, Tengzhou City was chosen purposefully as our primary data collection area.

Tengzhou, situated in the southern part of Shandong Province, is a county-level city covering approximately 1,495 km2, with a resident population of around 1.73 million. Nestled within the Huaihe River basin and the Beijing-Hangzhou Grand Canal water system, Tengzhou boasts fertile soil and unique conditions conducive to potato cultivation. This geographical advantage has established it as a crucial agricultural production region, often acknowledged as "The home of the Chinese

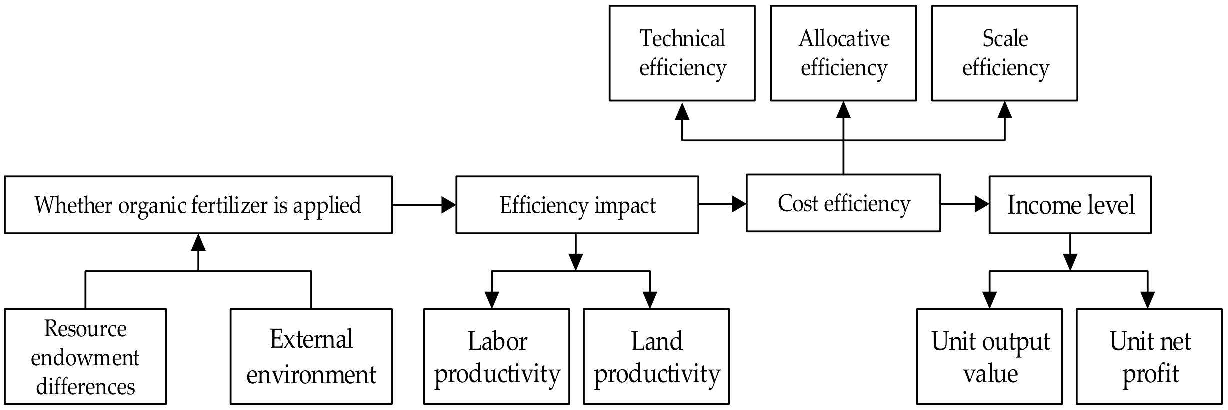

FIGURE 1
The conceptual framework for analyzing the economic effects of organic fertilizer application.

potato" (Zheng et al., 2023). According to Xinhua Silk Road (Xinhua Silk Road, 2023), with a nearly century-old history of potato plantation, Tengzhou is also referred to as the hometown of potatoes in China.

The projected potato cultivation area in Tengzhou City is expected to reach approximately 30,300 hectares by 2023. Furthermore, there has been widespread local promotion of advanced cultivation techniques, such as "two potatoes and one dish" and "two potatoes and one grain." Consequently, farmers predominantly engage in intensive cultivation to achieve high potato yields, recognizing the substantial investment costs associated with large-scale farming operations. The core planting areas in Tengzhou typically yield between 60,000 to 75,000 kg per hectare, positioning them among China's most productive regions for potato production.

In the third stage of our sampling process, we employed the method of probability proportional to size sampling (Rosén, 1997) to ensure a representative sample of Tengzhou City's potato farming landscape. Initially, we identified and randomly selected six townships: Jiehe Town, Dawu Town, Jiangtun Town, Longyang Town, Dongguo Town, and Jisuo Town, out of a total of 16 townships in the region. These six townships were chosen based on their cumulative contribution, which accounts for an impressive 79.21% of the entire potato planting area of approximately 24,000 hectares across Tengzhou City. Following the township selection, we proceeded to sample villages within each selected township. Five sample villages were chosen per township, totaling 30 villages across all six townships. From these villages, we applied a systematic random sampling method to select between 15 to 20 households per village. This approach ensured that the sample of households was both comprehensive and unbiased. Ultimately, we conducted face-to-face interviews with a total of 560 farmers selected from the sampled households. Through rigorous adherence to a structured questionnaire, we gathered data on various aspects of potato farming practices, challenges faced by farmers, and their perspectives on agricultural policies and innovations. The interviews yielded 508 responses meeting the criteria for completeness and accuracy.

3.2 Variable selection

3.2.1 Treatment variable

The paper focuses on the economic impact of organic fertilizer application by potato growers, with particular emphasis on their current practices. Therefore, the key variable in this study is the status of organic fertilizer application by growers. To assess this condition accurately, a specific indicator question was designed: "Does your family apply organic fertilizers?" The response options were coded as 1 for "yes" and 0 for "no."

3.2.2 Outcome variable

The improvement of the economic effect through organic fertilizer application is assessed based on research design, with five indicators including production technology efficiency and unit net profit as outcome variables.

3.2.3 Control variable

Previous studies show that farmers' individual characteristics, operational attributes, cognitive traits, and environmental factors significantly influence the economic outcomes of using organic fertilizers. Differences in gender, age, and education affect growers' understanding (Xie and Huang, 2021). Operational features like duration, income distribution, and labor force size impact their needs and abilities (Mathur et al., 2016). Knowledge of fertilization, environmental policies, and training enhances their comprehension application (Wang et al., 2019; Fan P. et al., 2023). Environmental factors such as fertility level and market distance also influence adoption (Naher et al., 2021). This study uses four control variables: individual characteristics, operational features, cognitive traits, and orchard environmental features, alongside factors for propensity score matching (Oyetunde-Usman et al., 2021; Daadi and Latacz-Lohmann, 2021b). The variables and their descriptions are presented in Table 1.[1]

3.3 Model building

To assess the impact of organic fertilizer application by growers, this study employs propensity score matching (PSM) methodology to account for heterogeneity between growers who apply organic fertilizers and those who do not (Wordofa et al., 2021). The objective is to ascertain whether organic fertilizer application influences production efficiency and planting income.

3.3.1 Multivariate linear regression model

$$Y_i = \beta_0 + \alpha\eta + \beta_i X_i + e_i \qquad (1)$$

The dependent variable Y_i in Equation 1 stands for the i the grower's potato production efficiency or planting benefits; η stands for the dummy variable. When $\eta = 1$, it indicates that the grower applies organic fertilizers, otherwise $\eta = 0$. X_i stands for the control variable. $\beta_0$and $e_i$respectively stand for the intercept term and residual term. α and βstand for coefficients to be estimated of explanatory variables.

3.3.2 Propensity score matching model

In the empirical analysis, matching methods can be divided into covariate matching and propensity score matching (PSM), with the latter being an improvement of the former (Fortin et al., 2021). However, to accurately measure the production efficiency and planting benefits of growers who fertilizers versus those who do not, this study employs the propensity score matching (PSM) model to construct a counterfactual framework for estimating the application of organic fertilizers. By comparing the differences in production efficiency and planting benefits between these two groups this study utilizes propensity matching to mitigate sample selection bias caused by "self-selection." Specifically, it identifies a group of potato growers who do not use organic fertilizers but possess similar resource endowment characteristics as those who do, in order to obtain an accurate assessment of the actual effects of organic fertilizer application.

Rosenbaum and Rubin (1983) proposed the concept of Propensity Score as: the propensity score of individual i is the

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[1] Production technical efficiency is the ratio of the actual output of the production unit measured from the perspective investment's output to the maximum potential output. The paper calculates the technical efficiency of potato planting in the region with MaxDEA software.

TABLE 1 Variable meaning and descriptive statistics.

Variable name	Meaning and variable assignment	Mean value	Standard deviation
Treatment variable			
Whether apply organic fertilizer	Whether apply organic fertilizer: 1 = yes, 0 = no	0.930	0.412
Result variable			
Labor productivity	Calculated on the basis of *per capita* potato output in of growers 2022 (kg/person)	8235.429	7099.039
Land productivity	Calculated on the basis of unit average potato output of growers in 2022 (kg/ha)	48941.450	11395.950
Production technical efficiency	Calculated on the basis of investment output function in 2022	0.687	0.518
Unit output	Calculated on the basis of unit total potato output in 20,222 (10,000 yuan/ha)	11.841	2.824
Unit net profit	Calculated on the basis of unit net profit of potato growers in 2022 (10,000 yuan/ha)	5.365	2.716
Control variable			
Individual features of respondents			
Gender	0 = female 1 = male	0.676	0.676
Age	Respondents' age in 2022 (full year of life)	51.050	9.574
Education background	Respondent's education (year)	11.10	3.799
Production and operation feature			
Planting scale	Actual potato planting area in 2022 (ha)	0.918	0.829
Planting period	Actual year of potato planting	17.537	7.634
Degree of specialization	The proportion of potato production income in family total income in 2022 (%)	0.788	0.132
Employed labor number	Family labor number (person)	3.396	1.453
Cognitive feature of respondent			
Understanding the hazard of excessive fertilization	Do you know the hazard of excessive fertilization: 1 = totally not understand, 2 = not understand, 3 = mediocre degree of understanding, 4 = understand a lot, 5 = understand it very well	3.337	0.965
Understanding of policies of soil and environmental protection	Do you know the policies related to soil and environment protection: 1 = totally not understand, 2 = not understand, 3 = mediocre degree of understanding, 4 = understand a lot, 5 = understand it very well	2.822	0.952
Training condition of organic fertilizer application	How often did you participate in trainings related to planting technology: 1 = never participate in, 2 = seldom participate in, 3 = often participate in	1.832	0.662
Environmental features of the orchard			
Degree of fertility of the soil	What is the degree of fertility of the orchard's soil: Poor = 1, Mediocre = 2, Good = 3	1.947	0.698
Dispersive degree	What is the dispersive degree of fragmentation of the orchard's parcels: Compact = 1, Relatively compact = 2, Incompact = 3	2.040	0.681
Distance between the place of production and the market	How far is the orchard from the market: Near = 1, Relatively near = 2, Relatively far = 3	2.348	0.683

conditional probability that individual *i* enters the treatment group given X_i, The propensity score is a one-dimensional variable with a value between [0.1], which reduces the dimensions of multiple covariates into one dimension and includes the information of all covariates. The basic principle of PSM is to assume that individuals choose whether to participate in a project based on observable characteristics, and unobservable characteristics will not affect whether individuals participate in a project. For individual *i* who participates in the project, non-participating items with the same observable characteristics are matched. As a better method than covariate matching, propensity score matching (PSM) has been widely used in sub-medicine, economic and policy evaluation. In recent years, it has become one of the most popular methods in the evaluation of policy effects (Wordofa et al., 2021). The specific steps are outlined as follows:

First of all, the Logit model is primarily employed to estimate the fitted value, i.e., the propensity score (PS value), representing the conditional probability of organic fertilizer application by each potato grower given their endowment feature X_i:

$$P(X_i) = P_r\left[D = 1 \middle| X_i\right] = \frac{\exp(\beta X_i)}{1 + \exp(\beta X_i)} i\epsilon\,(I + J) \qquad (2)$$

In the Equation 2, D represents the treatment variable. $D = 1$ means the grower applies organic fertilizers (treatment group I), and $D = 0$means the grower does not apply organic fertilizers (control group J). $X_i$stands for the matching variable that may influence the grower's application of organic fertilizers. Through estimating the Equation 2, the score, namely the possibility that the grower may apply organic fertilizers, is obtained.

Subsequently, five matching methods were and control groups were based on propensity scores of matching variables. The robustness of the matching result was confirmed if similar results were obtained across different methods. Afterwards, the study computes the average treatment effects (ATT) of both the treatment group and control group, thereby validating the impact of organic fertilizer application on potato planting efficiency and yield benefits. The specific model is presented as follows in Equation 3:

$$ATT = E\left[Y_1^i - Y_0^i\right] = E\left[Y_1^i - Y_0^i \middle| D=1\right] = E\left[Y_1^i \middle| D=1\right] - E\left[Y_1^i \middle| D=0\right]$$
$$i\epsilon\left(I+J\right) \qquad (3)$$

In the Equation 3, Y_1^i and Y_0^i respectively stand for the production efficiency or planting benefits of growers applying organic fertilizers and those who do not apply organic fertilizers. Since only the production efficiency and planting income of farmers applying organic fertilizer can be observed in the actual investigation, namely $E\left[Y_1^i \middle| D=1\right]$. However, the production efficiency and planting income of farmers who applied organic fertilizer could not be observed when they did not apply organic fertilizer., namely $E\left[Y_0^i \middle| D=1\right]$. The method of propensity score matching can be used to find a group of growers who do not apply organic fertilizers and have features similar to those owned by growers who apply organic fertilizers to make a comparison between the two parts in terms of production efficiency and planting benefits and estimate the production efficiency and planting benefits $E\left[Y_0^i \middle| D=1\right]$ of the growers who apply organic fertilizers at the time when they do not apply organic fertilizers. In this way, the difference value between production efficiency and planting benefits $E\left[Y_0^i \middle| D=1\right]$ and the estimated production efficiency and planting benefits $E\left[Y_0^i \middle| D=1\right]$ can be obtained, and the economic effect brought by organic fertilizer application to production efficiency and planting benefits of potato planting can be obtained.

3.3.3 Decomposition model of new cost efficiency

Data Envelopment Analysis (DEA), also known as the data envelopment model, encompasses the traditional concept of cost efficiency proposed into technical efficiency and allocative efficiency (Xue et al., 2020). However, when the invested values differ, the efficiency of different decision-making units may paradoxically be equal, which contradicts the principle of cost minimization. To address the limitations of traditional cost efficiency measures, this study employs a novel approach that accounts for varying prices of invested elements to calculate cost efficiencies across decision-making units with distinct unit costs resulting from disparate element prices (Tone, 2002). The basic idea is to decompose the actual investment cost into Minimum invested cost (optimal invested cost) + inefficient loss of the invested technology + inefficient loss of the price + inefficient loss of the allocation.[2]

Whereas t is set there are n decision-making units (DMU), x_o production investments and y_o outputs. The number of the invested elements of specific DMU (x_o, y_o) is x_{iO}, and its price is c_{iO}. Then the actual invested cost C_O can be presented as follows:

$$C_O = \sum_{i=1}^{m} c_{iO} x_{iO} \left(o = 1, \ldots, n\right) \qquad (4)$$

In regard to the production-possibility set P of traditional cost efficiency:

$$P = \left\{(x,y) | x \geq X\lambda,\ y \leq Y\lambda,\ \lambda \geq 0, X = \left(x_{1,} \ldots x_{n,}\right),\ Y = \left(y_{1,} \ldots y_{n,}\right)\right\} \qquad (5)$$

The investment-oriented CCR-I model is operated to obtain the optimal investment quantity x_{io}^* of DMU₀, and the target cost C_O^* of technical efficiency investment can be presented as follows:

$$C_O^* = \sum_{i=1}^{m} c_{iO} x_{io}^* \left(o = 1, \ldots, n\right) \qquad (6)$$

Then the loss L_O^* of inefficient technology invested can be presented as follows:

$$L_O^* = C_O - C_O^* \left(L_O^* \geq 0\right) \qquad (7)$$

3.3.4 Inefficient loss of the price

The study makes the efficiently invested quantity x* multiply by the actual price c to obtain the equation, $\overline{x}_{ij} = c_{ij} x_{ij}^*$, and combines $\overline{x}_{ij}$ with the output data to form a new production-possibility set. The investment-oriented CCR-I model is operated on the basis of the new data set, and the obtained target investment value in the column of technical efficiency values is used to calculate the target cost C_O^{**} of technical price efficiency. Then the inefficient loss of price L_O^{**} can be presented as follows:

$$L_O^{**} = C_O^* - C_O^{**} \left(L_O^{**} \geq 0\right) \qquad (8)$$

3.3.5 Inefficient loss of the allocation

The study decomposes the efficient investment shown in the datasheet of Step II as quantity and price, and the data of the decomposed quantity and price are applied to the new cost efficiency model. Then it adds the optimal invested costs C_O^{***} of each DMU in the target value together to obtain the optimal invested cost. Then the loss L_O^{***} caused by inefficient allocation can be presented as follows:

$$L_O^{***} = C_O^{**} - C_O^{***} \left(L_O^{***} \geq 0\right) \qquad (9)$$

3.3.6 Decomposition of actual invested cost and new cost efficiency

At last, based on the aforesaid decomposition, the actual invested cost (C₀) can be decomposed as follows:

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[2] Inefficient loss of the invested technology refers to the inefficient investment caused by the actual investment higher than the optimal cost due to the lagging technology. Inefficient loss of the price refers to the inefficient investment caused by the optimal invested cost of the decision-making unit calculated on the basis of the actual price higher than the optimal invested cost calculated on the basis of the initial price due the rise of the price. Inefficient loss of the allocation refers to the inefficient investment caused by the optimal invested cost of the decision-making unit higher than the optimal invested combination due to the ineffective market allocation.

$$\text{Average actual invested cost } (C_O) = \text{Optimal investment cost } (C_O^{***}) + \text{Inefficient loss of the invested technology } (L_O^{*}) + \text{Inefficient loss of the price } (L_O^{**}) + \text{Inefficient loss of the allocation } (L_O^{***}) \quad (10).$$

$$\text{New cost efficiency (CE)} = \text{Technical efficiency (TE)} \times \text{Allocative efficiency (AE)} \times \text{Scale efficiency} \quad (11).$$

4 Results

4.1 Analysis of the grower operational effect of organic fertilizer application

To assess the economic impact resulting from the application of organic fertilizers by growers, this study employs ordinary least squares (OLS) regression analysis based on Equation 1, without accounting for heterogeneity. The results (Table 2) reveal that the utilization of organic fertilizers exerts a significant and positive influence on various indicators, including labor productivity (755.02 ha/person), land productivity (3379.65 kg/ha), production technical efficiency (1.8%), unit output (6609.06 yuan/ha), and unit net profit (4824.08 yuan/ha).

4.2 Analysis of influencing factors of organic fertilizer adoption by growers

Initially, the study employs the Logit model to estimate the propensity score and identify the matching variable that significantly influences growers' application Subsequently, a stepwise regression method is employed to eliminate variables with no significant impact on growers' organic fertilizer application in models I-V. Finally, 8 control variables such as growers' educational background and planting scale are selected as matching variables, and these results are presented in model V as depicted in Table 3.

In terms of individual characteristics of growers, at a significant level of 10%, the educational background positively influences the application of organic fertilizers by growers. This suggests that growers with a higher level of education, who prioritize land and demonstrate a better comprehension of green agricultural policies, are more inclined to utilize organic fertilizer (Blanchard et al., 2013).

Concerning growers' features of production and operation, at the significance level of 5%, the planting scale has a negative influence on growers' organic fertilizer application. The possible reason may be that growers with a larger scale of production have scattered land parcels, and the behavior of organic fertilizer application is easily influenced by adverse factors, such as the high cost of transportation. At the significance level of 5%, the planting period also has a negative influence on growers' behavior of organic fertilizer application. The reason may be that more elements are required to be invested in organic fertilizer application. Although growers with long-term experience in growing potatoes have abundant planting experience, they may not be proficient in adopting new technology. The various elements invested may impede the increase of production efficiency and income of potato planting. Therefore, the longer the planting period, the weaker the growers' willingness to organic fertilizer application.

At the significance level of 1%, the degree of specialization has a positive influence on growers' behavior of organic fertilizer application. In other words, growers with the income of potato production sharing a higher proportion of the family's total income are more likely to apply organic fertilizers. The reason may be that growers who are more specialized can be more dedicated when they engage in agricultural production, and they generally hope to improve the planting benefits of potato planting by improving production efficiency.

In terms of growers' cognitive features, at the significance level of 5%, understanding the hazards of excessive fertilization has a positive influence on growers' behavior of organic fertilizer application. This suggests that growers recognize the potential long-term harm to soil and the environment resulting from excessive fertilization. They acknowledge that adopting organic fertilizers can mitigate these adverse impacts. Consequently, a deeper understanding of the hazards associated with excessive fertilization enhances their comprehension of environmental protection and promotes more effective utilization of organic fertilizers.

At the significance level of 10%, understanding policies related to soil and environmental protection has a positive influence on growers' behavior of organic fertilizer application. Through strengthening the publicity of policies related to soil and environment protection and governance, the government and relevant departments can deepen growers' understanding of soil and environmental protection. This can encourage them to engage in the behavior of green production and apply organic fertilizers.

At the significance level of 1%, professional training in organic fertilizer application has a positive influence on growers' behavior of organic fertilizer application. This indicates that professional training can convey technical information related to organic fertilizer application, reduce the risk of adopting new technology, enhance growers' ability, and foster their awareness of scientific fertilization (Liao and Chen, 2017). Additionally, professional training can help growers master the correct methods of organic fertilizer application, reduce the cost of unit production, and encourage growers to make the decision of organic fertilizer application by improving quality, efficiency, and growers' planting benefits.

At the significance level of 5%, the degree of fertility of the soil among the environmental characteristics of orchards has a negative influence on growers' behavior of organic fertilizer application. In other words, growers facing more infertile soil are more likely to apply organic fertilizers (Salam et al., 2021). The reason may be that organic fertilizers' prices are high, and their effects can only be slowly shown. When growers perceive their soil as fertile, they tend to reduce organic fertilizer application to save the cost of fertilization.

4.3 Empirical result analysis of propensity score matching

4.3.1 K value matching

The k-nearest Neighbor matching method is employed for the preliminary analysis. Initially, the analysis is conducted using k-nearest neighbor matching with three different matching ratios (refer to Table 4, 5). Simultaneously, the study utilizes the Bootstrap

TABLE 2 Multiple linear regression models were used to estimate the results.

Variable name	Labor productivity	Land productivity	Production technical efficiency	Unit output	Unit net profit
Application of organic fertilizer	755.017*** (237.203)	3379.652** (1259.224)	0.018** (0.009)	6609.057* (3390.834)	4824.075* (2565.914)
Gender	−304.548 (204.253)	−2088.846 (1055.466)	−0.005 (0.005)	−4646.883 (3518.495)	−4132.572 (3489.567)
Age	−15.260 (11.618)	−60.954 (60.035)	−0.001 (0.001)	−270.568 (243.251)	−316.880 (241.606)
Education background	22.248 (27.142)	31.198 (140.256)	0.001 (0.001)	19.646 (334.671)	59.269 (330.827)
Planting scale	9370.596*** (145.268)	3363.178* (1750.664)	0.006* (0.004)	11427.530* (10791.192)	8637.783** (3770.618)
Planting period	−1.154 (14.348)	−56.872 (74.144)	0.001 (0.001)	−26.047 (176.918)	−5.842 (24.886)
Degree of specialization	953.897 (1211.775)	6904.187 (6261.790)	0.039 (0.030)	13645.790 (14941.530)	7853.194 (10769.920)
Employed labor number	1224.108 (864.904)	168.331 (335.390)	0.001 (0.002)	857.909 (800.288)	420.017 (791.096)
Understanding the hazard of excessive fertilization	65.206** (28.638)	656.359** (261.379)	0.013** (0.006)	1421.219** (639.531)	1162.428** (464.145)
Understanding of policies of soil and environmental protection	52.594* (29.246)	236.3655** (94.522)	0.0014* (0.008)	765.517* (406.030)	799.367* (443.558)
Training condition of organic fertilizer application	72.919** (36.301)	860.040*** (159.354)	0.017*** (0.004)	1738.561** (6450.542)	−1478.807*** (326.989)
Degree of fertility of the soil	−360.181* (202.531)	−1212.409* (788.195)	−0.008* (0.004)	−2438.962** (1180.747)	−2232.267* (1259.145)
Dispersive degree	46.536 (150.047)	1508.339 (775.363)	0.001 (0.004)	3208.676 (2850.127)	3229.687 (2828.876)
Distance between the place of production and the market	−29.309 (151.005)	−63.475 (780.309)	−0.004 (0.004)	−690.248 (1861.931)	−896.500 (1840.545)
Constant	6643.029*** (1175.589)	49715.981*** (6074.803)	0.143** (0.064)	103634.100*** (14495.360)	36159.150*** (11328.860)

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

TABLE 3 The estimation results of the decision equation for growers to apply organic fertilizer based on the Logit model.

Variable name	Model I	Model II	Model III	Model IV	Model V
Gender	−0.668 (0.954)	−0.770 (0.875)	−1.087 (0.857)	−1.094 (0.854)	–
Age	−0.058 (0.052)	−0.048 (0.048)	0.045 (0.051)	0.047 (0.052)	–
Education background	0.331* (0.195)	0.389* (0.217)	0.323* (0.152)	0.311* (0.161)	0.291* (0.155)
Planting scale	−2.322** (0.822)	−2.068** (0.934)	−2.049** (0.728)	−1.981** (0.892)	−2.068** (0.931)
Planting period	−0.164** (0.076)	−0.154** (0.070)	−0.154** (0.072)	−0.153** (0.072)	−0.170** (0.077)
Degree of specialization	60.609*** (12.809)	59.299*** (12.064)	58.249*** (11.399)	58.277*** (11.411)	56.869*** (10.852)
Employed labor number	0.176 (0.264)	0.107 (0.262)	−0.062 (0.257)	–	–
Understanding the hazard of excessive fertilization	1.552** (0.585)	1.476** (0.557)	1.489** (0.561)	1.491** (0.563)	1.500** (0.540)
Understanding of policies of soil and environmental protection	1.444* (0.850)	1.451* (0.801)	1.321* (0.607)	1.335* (0.710)	1.457* (0.771)
Training condition of organic fertilizer application	2.988*** (0.811)	2.614*** (0.691)	2.625*** (0.679)	2.623*** (0.681)	2.749*** (0.693)
Degree of fertility of the soil	−3.032** (1.135)	−2.642** (1.024)	−2.777** (1.171)	−2.747** (1.233)	−2.423** (0.995)
Dispersive degree	−1.018 (0.678)	−0.904 (0.621)		–	–
Distance between the place of production and the market	1.051 (0.764)	–	–	–	–
Constant	−59.728*** (13.588)	−56.168*** (12.330)	−56.009*** (11.766)	−55.691*** (11.6769)	−52.449*** (10.460)

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

TABLE 4 Comparison of results calculated using different nearest neighbor matching.

Matching method	Labor productivity	Land productivity	Production technical efficiency	Unit output	Unit net profit
1:1	1572.589***	16988.880*	0.040*	36978.773*	15626.173*
1:3	1363.465***	14566.693**	0.016*	31922.622*	17068.089*
1:4	973.764***	8821.973*	0.015*	36220.540*	13048.290*

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

TABLE 5 PSM matching results.

	Sample not matched	matched sample	Total
Control group	14	104	118
Treatment group	75	353	428
Total	89	457	546

method to select neighbor matching with a 1:3 ratio based on critical values generated from data under conditions of small or medium-sized samples.

4.3.2 Overlap inspection

The study assesses the balance between the treatment group and the control group by comparing the matching variables before and after matching. Table 6 reveals that the *p*-values for various variables significantly increase after matching, and the inspection results are not significant. This indicates that the matching has a positive effect, validating the rationality and effectiveness of the matching process.

4.3.3 Balance inspection

To ensure result accuracy, the study adopts the method proposed by Jiang B. et al. (2023) as a reference and utilizes parameters such as

TABLE 6 Balance hypothesis testing before and after propensity matching.

Variable name	Unmatched matched	Mean		%bias	%Reduct |bias|	*P*-value
		Treated	Control			
Education background	U	11.709	8.913	77.1	78.4	0. 000
	M	10.485	11.088	−16.6		0.216
Planting scale	U	0.968	0.735	31.2	−176.0	0.007
	M	1.140	1.785	−86.2		0.744
Planting period	U	17.386	18.085	−9.1	−115.6	0.037
	M	15.846	14.337	19.6		0.201
Degree of specialization	U	0.844	0.585	264.6	82.2	0.000
	M	0.783	0.828	−45.5		0.535
Understanding the hazard of excessive fertilization	U	3.565	2.509	124.0	9.5	0.000
	M	3.093	2.137	112.2		0.886
Understanding of policies of soil and environmental protection	U	3.028	2.076	113.4	68.5	0.000
	M	2.640	2.940	−35.7		0.110
Training condition of organic fertilizer application	U	1.650	2.492	−142.4	26.0	0.000
	M	1.813	2.437	−105.4		0.655
Degree of fertility of the soil	U	2.058	1.542	81.2	59.3	0.000
	M	1.773	1.983	−33.0		0.183

pseudo R2, the test value of the likelihood ratio, Mean Bias, etc., to assess the matching quality of different matching methods (refer to Table 7). The findings demonstrate a notable improvement in matching quality:

- Pseudo R^2 decreases from 0.901 before matching to 0.004–0.005.
- The test value of the likelihood ratio decreases from 513.31 before matching to 14.61–19.94.
- Mean Bias decreases from 105.4 to 4.9–9.8%.
- Median Bias decreases from 97.3 to 2.8–6.5%.
- B-value decreases from 3318.3 before matching to 19.8–13.1, which is 20 lower than the boundary line's standard.

The variation in these indicators before and after matching indicates that systematic differences between the treatment group and the control group, caused by disparities in observable variables, are essentially eliminated after propensity matching. The matching quality of the model is deemed good. The results across the five types of matching methods are relatively consistent, affirming the robustness of the balance inspection results.

4.3.4 Sensitivity analysis

The key hypothesis to support the PSM method is that growers only depend on observable variables to make the decision of organic fertilizer application. Although as much as matching variables are selected in the paper, there are still some unobservable factors that may influence growers' decisions about organic fertilizer application. Therefore, relying on the research methods proposed by Zhao et al. (2021) and Ren et al. (2021), the study adopts Rosenbaum's boundary method to conduct sensitivity analysis, and the result is shown in Table 8. The parameter gamma (≥ 1) refers to the measurement of the degree of deviation freedom of (gamma = 1) without the condition of concealing bias. The larger the gamma value is, the lower the degree of sensitivity is, and the result can be more robust. According to the documents, the researchers conduct sensitivity analysis within gamma's range between 1 and 2 (Dillon, 2011). During the process of analyzing the influence of organic fertilizer application on growers' economic effect, it is shown that both sig + and sig- are 0, indicating that unobservable factors are not sensitive to the influence of the result of estimation, which has a certain robustness.

4.3.5 Average treatment effect estimates

The use of multiple matching methods helps ensure the reliability and validity of the findings (Pirracchio et al., 2016). By comparing various matching techniques, we can be more confident that the observed effects are genuinely due to the organic fertilizer application and not artifacts of a particular matching method. Additionally, the robustness test helps identify any potential biases or inconsistencies across different methods, providing a more comprehensive understanding of the treatment effect (Abdia et al., 2017). Thus, to further verify the estimated results of the above-mentioned k-nearest neighbor matching, five additional methods, including k-Nearest neighbor matching, radius matching, K-nearest neighbor matching within calipers, Kernel Matching and Local linear regression matching, were adopted for a robustness test. This involved comparing the results (production efficiency and planting benefit) between matched groups to obtain the average treatment effect (ATT) of the five outcome variables, thereby confirming the impact of organic fertilizer application (Table 9).

The estimated results presented in Table 9 indicate that the outcomes from the five matching methods are consistent with each other. This suggests that the research findings possess proper robustness, affirming that organic fertilizer application indeed has a significant and positive influence on planting outcomes. Regarding production efficiency, the Average Treatment Effect on the Treated (ATT) of the treatment group's labor productivity is 1588.47 kilograms per person. This signifies that the *per capita* potato output of growers who apply organic fertilizers increases by 1363.47–1829.07 kilograms, and it is statistically significant at the 1% level. Similarly, the average ATT of land productivity is 16346.77 kilograms per hectare, indicating

TABLE 7 Matching quality test of different matching methods.

	Matching methods	Ps R^2	LR chi2	Mean Bias(%)	Med Bias(%)	B-value
Unmatched		0.901	513.31	105.4	97.3	318.3
Matched	k-Nearest neighbor matching	0.004	19.94	6.8	4.6	13.1
	Radius matching	0.005	14.61	7.9	5.2	17.2
	K-nearest neighbor matching within calipers	0.005	16.88	9.8	2.8	12.9
	Kernel Matching	0.005	18.66	5.1	6.5	19.8
	Local linear regression matching	0.005	16.38	4.9	5.8	13.9

***, ** and *represent significant at levels of 1, 5 and 10%, respectively. The caliper range of Radius matching was 0. 01, the K-Nearest neighbor matching within the caliper was 1 : 3 matching with the caliper range of 0. 01, Kernel matching uses the default bandwidth of 0. 06.

TABLE 8 Rosenbaum bounds sensitivity analysis.

Gamma	sig+	sig-
1	0	0
1.1	0	0
1.2	0	0
1.3	0	0
1.4	0	0
1.5	0	0
1.6	0	0
1.7	0	0
1.8	0	0
1.9	0	0
2	0	0

a significant increase in potato output per hectare for growers who apply organic fertilizers (14566.69–15318.09 kilograms) at the 10% significance level. This validates Hypothesis H1.

The average ATT coefficient of production technical efficiency's net effect is 0.036, indicating a noticeable increase in production technical efficiency by 1.6–5.0%. This result is statistically significant at the 10% level, verifying Hypothesis H2. Concerning planting benefits, organic fertilizer application exhibits a clear promotional effect on unit output and unit net profit for growers. The average ATT of unit output is 35011.12 yuan per hectare, signifying a significant increase in the total potato output for growers who apply organic fertilizers (31922.62–337475.48 yuan) at the 10% significance level. Similarly, the ATT of unit net profit is 16135.32 yuan per hectare, indicating a substantial increase in potato net profit per hectare for growers who apply organic fertilizers (12641.78–118325.94 yuan) and is significant at the 10% level. This verifies Hypothesis H3.

4.4 Decomposition result of the new cost efficiency

Since different types of growers are mainly limited by their resource endowment when choosing technology, they tend to pursue production factors, family resources and other allocations for optimization to achieve maximum efficiency. Therefore, when facing the real problems of the small planting scale, multiple parcels, and growers with different planting scales have different motivations for adoption and operational costs, which usually influence the decision of organic fertilizer application (Adnan et al., 2017b).

The paper uses MAXDEA7.0 software to decompose the cost efficiency of organic fertilizer application of growers with different scales of planting. This study builds upon the research conducted by Du et al. (2022) and examines the potato planting scale of farmers in Tengzhou City through field investigations. Through extensive discussions with local agricultural technology experts and farmers, it was determined that 0.667 ha and 1.333 ha are widely accepted benchmarks for categorizing farm sizes in the region. Accordingly, this paper defines small-scale farmers as those with a potato planting area less than 0.667 ha, medium-scale farmers as those with a potato planting area between 0.667 ha (inclusive) and 1.333 ha (exclusive), and large-scale farmers as those with a potato planting area exceeding 1.333 ha. This study also calculated the average cost of organic fertilizer applied to production investments of different planting scales, taking the average yield as output, and put it into Equations 4-9, obtaining the following decomposition results: the average actual invested cost (C_O), target cost of efficient invested technology (C_O^*), target cost of efficient technology and price (C_O^{**}), optimal investment cost (C_O^{***}), inefficient loss of the invested technology (L_O^*), inefficient loss of the price (L_O^{**}), inefficient loss of the allocation (L_O^{***}), cost efficiency (CE), technical efficiency (TE), allocative efficiency (AE) and scale efficiency (SE) (Table 10).

It can be seen from Table 10 that compared with the optimal cost invested C_O^{***}, the average cost $C_O$invested by growers who apply organic fertilizers includes an inefficient loss reaching 1949.42 yuan. The inefficient loss of the invested technology L_O^* is 5440.96 yuan. The inefficient loss of the price L_O^{**} is 1350.27 yuan, and the inefficient loss of the allocation L_O^{***} is 1304.41 yuan. Therefore, the inefficiency loss of invested technology accounts for 67.21% of the total loss, indicating that the inefficiency in technology investment is primarily responsible for the inefficient cost loss in potato production in 2022. In conditions where soil organic matter decreases and nutrient balance is disrupted, crop absorption of nutrients from chemical fertilizers becomes challenging, potentially leading to excessive fertilizer application. However, incorporating organic fertilizer positively impacts the flexibility of chemical fertilizers' output. The continuous use of organic fertilizer helps mitigate ineffective input technology losses and promotes long-term cost savings and efficiency improvements within the potato industry.

Upon comparing the cost efficiency of growers with different planting scales, a notable pattern emerges. Farmers with small scales ranging from 0.667 to 1.333 hectares exhibit higher values in terms of cost efficiency, technical efficiency, allocative efficiency, and scale efficiency compared to those with smaller or larger planting scales. In contrast, growers with planting scales smaller than 0.267 hectares and over 0.533 hectares demonstrate relatively lower values in the mentioned efficiencies. This implies that the production efficiency indicators, including cost efficiency, technical efficiency, allocative efficiency, and scale efficiency, for growers with planting scales of 0.267–0.533 hectares are higher than those for growers with planting scales smaller than 0.267 hectares and over 0.533 hectares (refer to Table 10). In other words, there is an inverted U-shaped trend between the planting scales of sample growers and various aspects of production efficiency (Salam et al., 2021; Niu et al., 2023). This verifies Hypothesis H4.

5 Discussion

The utilization of agrochemicals such as synthetic fertilizers in modern agriculture has yielded benefits but also poses risks to human health and the environment (Wang et al., 2018). Overuse of chemical fertilizers has significantly impacted the ecosystem of farmlands, human health, and the achievement of sustainable development goals (Patra et al., 2016). Addressing the presence of these chemicals, which include harmful components like nitrites, NH4+ (ammonium ion), and PM2.5 (fine airborne particles), is crucial in the face of today's triple planetary crisis of climate change, biodiversity loss, and pollution (Naidu et al., 2021). These crises threaten to undo decades of human development progress (Srivastav, 2020). Over the past century, the volume of synthetic nitrogen compounds in water, soil, and the atmosphere has doubled, largely due to the widespread adoption of synthetic fertilizers (Tyagi et al., 2022). The current deviation from Sustainable Development Goals (SDGs) underscores the severity of this issue. Despite its complexities and challenges, effective management of chemicals and waste is essential for building resilient and healthier food systems (Ladha et al., 2020). Exposure to certain chemicals can pose serious health risks, including cancer, reproductive and developmental disorders, and neurological issues (Sharma and Singhvi, 2017). In particular, the latest Global Chemicals Outlook from the UN Environment Program (UNEP) alerts to escalating risks linked to the use of hazardous chemical fertilizers and their potential to contaminate other natural resources such as water, air, and soil (Alpizar et al., 2019).

Nitrogen is crucial for sustaining life on Earth, yet its excessive presence poses significant dangers as a pollutant, contaminating water bodies, plants, and animals, and threatening public health (Bijay-Singh and Craswell, 2021). Despite its low public visibility, experts highlight the inundation of excess nitrogen as one of today's most pressing pollution challenges (Mashamaite et al., 2024). According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), nutrient runoff from farms, often laden with synthetic fertilizers, has notably disrupted land ecosystems (IPBES, 2019). However, freshwater and marine environments have suffered the most severe impacts (Micella et al., 2024).

The key to the current soil and water conservation problems is not the lack of fertility, but the lack of organic matter and microbial bacteria (Savci, 2012), which not only poses a major threat to food security but also significantly hinders the national food safety (Ma et al., 2014). Continuous use of chemical fertilizers leads to soil degradation and diminishes crop productivity. Chemical fertilizers have little impact on the restoration of soil fertility (Bisane et al., 2023). The compaction of soil occurs due to the persistent use of chemical fertilizers. Consequently, this gives rise to other problems such as inadequate oxygenation, subpar water drainage, and the erosion of soil. Additionally, it leads to reduced permeability, hydraulic conductivity, and groundwater recharge (Pahalvi et al., 2021). On the contrary, organic fertilizer, being an exemplary green agricultural technology, primarily functions to supplement soil organic matter, enhance crop root vitality, balance nutrient levels, and improve potato quality (Zheng et al., 2024). By enriching the soil with organic matter, organic fertilizers foster a healthier and more sustainable ecosystem. They contribute to better soil structure, increased microbial activity, and improved nutrient retention, which are crucial for long-term soil fertility and productivity (Lin et al., 2024). In addition to environmental harm, human health is also imperiled. The serious consequences of chemical fertilizers on human health are already well-proven (Loan et al., 2018; Hossain et al., 2022), directly and indirectly, causing various fetal health issues (Nadarajan and Sukumaran, 2021) and posing a serious threat to achieving Chinas promises to achieve optimal sustainable development goals (Loan et al., 2018). Agricultural emissions of ammonia can interact with pollutants from vehicle exhausts, generating harmful particulate matter in the air that exacerbates respiratory diseases (Zhou et al., 2018).

The efficiency of chemical fertilizer application is not optimistic in a country like China (Chen Z. et al., 2022). Excessive chemical fertilizer input has led to serious excessive nitrate content in groundwater in the dryland production system in northern China, which has affected drinking water safety, while the paddy field production system in southern China has led to excessive nitrogen and phosphorus in surface water (Ji et al., 2023). However, China's agriculture has entered a phase of high-quality development. To achieve the transformation and upgrading of the potato industry, as well as promote its high-quality development, it is imperative to rely on the effective promotion of green agricultural technologies such as organic fertilizers. This will facilitate the transition of potato production toward a direction characterized by technological innovation, sustainable practices, industrial advancement, and increased productivity and income generation. In comparison to solely applying chemical fertilizers, adopting a combined approach of 'chemical fertilizers + organic fertilizers' proves more advantageous in augmenting potato yield (Naghdi et al., 2022). This is attributed to the decrease in soil organic matter content and nutrient imbalances, which hinder the absorption of nitrogen, phosphorus, potassium, and other fertilizer nutrients by crops, thereby potentially leading to excessive fertilizer application (Huang et al., 2021). Consequently, augmenting the utilization of organic fertilizers facilitates the enhancement of potato quality and ecological environment while fostering the establishment of an organic potato (Jiang L. et al., 2023).

The decomposition of the new cost-efficiency model reveals significant potential for reducing production costs or enhancing production efficiency in Tengzhou potatoes. Firstly, there is a possibility of achieving cost reduction or improved efficiency by focusing on enhancing technical and configuration aspects. Secondly, by considering the application of organic fertilizers or implementing appropriate scale control measures, there is even greater potential for achieving cost savings and improving production efficiency (Lu et al., 2019). From a technological efficiency perspective, reducing costs or enhancing production efficiency entails minimizing unnecessary inputs in the production process. However, due to farmers' extensive accumulation of long-term production experience, altering the existing production mode becomes challenging. Consequently, the government, cooperatives, and other relevant departments must provide increased guidance to farmers regarding the application of organic fertilizers, implementation of scientific planting techniques, and promotion of green agricultural technology. Through the comprehensive analysis presented in this article, significant potential still exists for cost reduction and enhanced competitiveness within potato production processes. However, considering the challenges associated with cost reduction, it is imperative to continue implementing agricultural support policies (such as providing financial assistance and subsidies) in the short term to facilitate environmentally sustainable potato production (Fan P. et al., 2023). As cost efficiency improves over time, a gradual reduction in agricultural protection should be pursued to mitigate potential fluctuations in production.

Relatively, the insufficient application of organic fertilizer is the most common phenomenon among farmers (Adnan et al., 2019a). The factors restricting their use of organic fertilizer extend beyond just the scale of operation and various costs. These factors also include the price of fertilizer, income level, risk preference, cognitive level, resource endowment, and other considerations (Chen et al., 2020). For example, in terms of cognition, farmers generally believe that organic fertilizer has low nutrient content, requires a large application rate, has a slow fertilizer effect, and does not provide a significant short-term yield increase. Compared to chemical fertilizers, the perception of organic fertilizer as having insufficient "fertilizer strength" is a key reason for the low enthusiasm among farmers to apply it (Luan et al., 2018). Regarding capital factors, farmers' low willingness to invest in green production may be influenced by constraints on their capital endowment (Wang H. et al., 2021). In terms of risk preference, the belief that replacing chemical fertilizer with organic fertilizer might reduce production leads farmers with higher risk aversion to applying more chemical fertilizer. They mostly prefer to avoid the potential production reduction associated with adopting organic fertilizers (Belete, 2022).

Specifically, for small-scale growers, limited access to resources such as division of labor, collaboration, and specialized inputs leads to a relatively weak inclination to adopt organic fertilizers (Marenya and Barrett, 2007). Despite significant manpower investments in potato fertilization, most small-scale farmer's lack enthusiasm for embracing green agricultural technologies like organic fertilizers to reduce expenses (Adebiyi et al., 2020). In rural China, the decentralized operation pattern results in a planting system dominated by scattered, fragmented plots. This fragmentation can cause conflicts among farmers due to differences in planting structures, and neighboring farmers may face high collective decision-making costs when adjusting planting structures or applying fertilizers uniformly (Xu et al., 2014). Additionally, the transportation of organic fertilizers poses challenges due to high costs, long distances, and short shelf life, impacting the environment and human health (Guo et al., 2024). Furthermore, small plots struggle to achieve the scale efficiency of agricultural mechanization, whereas large plots can leverage machinery to achieve economies of scale. Consequently, a combination of mechanization and labor is often employed in the planting process. The fragmented nature of agricultural plots can also lead to inefficiencies in resource utilization, pest and disease control, and overall productivity (Wang et al., 2016). Coordinating numerous smallholders to adopt best practices uniformly is challenging, leading to varied levels of technology adoption and agricultural output (Cui et al., 2018).

Therefore, high transportation costs and the environmental impact of moving organic fertilizers over long distances highlight the need for localized production and use of organic inputs. Developing localized organic fertilizer production facilities could mitigate these issues, reducing transportation costs and environmental impact while promoting sustainable agricultural practices (Zhang et al., 2021). Additionally, policies and initiatives aimed at consolidating land holdings or promoting cooperative farming could enhance agricultural efficiency and sustainability. Cooperative farming can help achieve economies of scale, reduce conflicts among farmers, and lower collective decision-making costs. It can also facilitate the uniform application of fertilizers and the adoption of mechanization, ultimately improving productivity and sustainability (Zhang et al., 2020). Moreover, investing in agricultural research and development to create more efficient and sustainable farming technologies is crucial. Innovations in organic fertilizer production, storage, and application could address the challenges posed by decentralized and fragmented farming systems (Liu et al., 2022). Training and support for farmers in adopting these new technologies and practices will be essential for their successful implementation. However, higher costs associated with utilizing and managing agricultural machinery result in lower efficiency in factor allocation, leading to relatively high costs for organic fertilizer application (Case et al., 2017). Moreover, labor scarcity can increase internal regulatory costs, hindering the achievement of intensive cultivation and precision farming practices, thereby reducing scale efficiency (Li F. et al., 2020; Fuller et al., 2021). Consequently, growers are more inclined to apply fertilizers on a larger scale to optimize cost savings and enhance efficiency. Potato, as an important food crop, can achieve optimal technical efficiency in organic fertilizer production only when combined with local realities and appropriate planting scales. This approach ensures that the benefits of organic fertilizers are maximized within the specific agricultural context.

Limitations on available resources and the state of the environment pose serious threats to long-term economic and social progress. The agriculture sector of any emerging country like China must pursue goals such as minimizing environmental pollution, contributing to environmental governance, and protecting the environment, especially given the severe resource and environmental restrictions it faces (Du et al., 2023). To address these challenges, China has launched several programs and policies to encourage sustainable agricultural growth (Yang et al., 2022). Since 2015, the Central Committee of the Chinese Communist Party (CCP) has taken significant measures to combat non-point source pollution in agriculture. A major turning point was the release of the "Opinions on Innovating Systems and Mechanisms to Promote Green Agricultural Development." This policy framework seeks to enhance the capacity for sustainable agricultural growth by establishing systems to prevent and control agricultural non-point source pollution (Liu et al., 2020, pp. 1978–2017; Shen et al., 2020). It also aims to position agriculture as an ecological barrier for a beautiful

TABLE 9 Results of average treatment effect (ATT) estimates for the outcome variables in 2022.

Matching methods	Labor productivity	Land productivity	Production technical efficiency	Unit output	Unit net profit
k-Nearest neighbor matching	1363.465***	14566.693*	0.016*	31922.622*	17068.089*
Radius matching	1520.406***	17595.137*	0.043*	37475.480*	18013.422*
K-nearest neighbor matching within calipers	1434.752***	17523.914*	0.050*	37371.086*	18325.943*
Kernel Matching	1829.071***	16729.996*	0.038*	36324.614*	14627.365*
Local linear regression matching	1794.640***	15318.087*	0.035*	31961.777*	12641.783*
Mean ATT	1588.467	16346.765	0.036	35011.116	16135.320

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

TABLE 10 Results of the new cost-efficiency decomposition calculated for the treatment group sample.

DMU	c_O	c_O^*	L_O^*	c_O^{**}	L_O^{**}	c_O^{***}	L_O^{***}	CE	TE	AE	SE
Lower than 0.667 hectares	27162.20	21504.16	5658.04	20070.55	1433.61	17788.65	2281.90	0.66	0.79	0.93	0.89
0.667–1.333 hectares	27569.75	22690.69	4879.06	21783.06	907.63	21109.78	673.28	0.77	0.82	0.96	0.97
Over 1.333 hectares	28412.46	22626.70	5785.76	20917.12	1709.57	19959.09	958.03	0.70	0.80	0.92	0.96
Mean	27714.80	22273.85	5440.95	20923.58	1350.27	19619.17	1304.40	0.71	0.80	0.94	0.94

China and contribute to building the foundation of eco-friendly rural development and revitalisation (Hou and Wang, 2022).

Seemingly, in 2017, the Ministry of Agriculture initiated environmentally friendly agricultural development initiatives (Han, 2019). Among these efforts was the recycling of polluting manure from cattle and poultry into organic fertilizers for crops like tea, fruit trees, and vegetables (Chen Z. et al., 2022). The objective was to decrease non-point source pollution, encourage the comprehensive treatment of agricultural production wastes, and limit the excessive use of agricultural resources (Yu et al., 2020). These measures aim to guide the agricultural sector toward environmentally friendly growth, aligning with the broader national objectives of protecting the environment and responsibly using resources (Lu et al., 2021). A key component of these eco-friendly development measures is the advocacy of organic fertilizers. When applied to soil, organic fertilizers improve crop quality, root vitality, nutrient balance, and soil organic matter content. They help reduce the negative effects of chemical fertilizers on the environment by promoting more balanced soil ecosystems. Enhanced soil structure, higher microbial activity, and greater nutrient retention are critical for long-term soil fertility and productivity (Wang H. et al., 2023; Zhu et al., 2024).

6 Conclusion

This study employs the Propensity Score Matching (PSM) model and a novel cost-efficiency decomposition method to evaluate the economic effects of applying organic fertilizer to potato facilities in Tengzhou City, Shandong Province. The key findings are as follows:

(i) Application of organic fertilizer significantly enhances the production efficiency of potato growers. Compared to the control group without organic fertilizer application, the use of organic fertilizer increases average production technical efficiency, labor productivity, and land productivity by 3.6%, 1588.47 kg/person, and 16346.77 kg/ha, respectively. Additionally, organic fertilizer application positively impacts potato planting benefits, leading to an average increase of 35011.12 yuan in output per hectare and 16135.32 yuan in net profit per hectare.

(ii) Analysis of cost efficiency among growers with different production scales reveals that those with a planting scale of 0.667 to 1.333 hectares exhibit relatively high production efficiency across various aspects. Furthermore, a notable inverted U-shaped trend is observed between planting scale and production efficiency.

(iii) Utilizing a novel cost efficiency decomposition method, it is determined that 67.21% of inefficient losses in invested costs can be attributed to technological inefficiencies. The application of organic fertilizer demonstrates significant potential in mitigating these technological inefficiencies. Moreover, the continuous implementation of organic fertilizer yields substantial long-term benefits, including cost reduction and efficiency enhancement for potato cultivation and other food crops.

Based on these findings, the following policy recommendations are proposed:

(i) Strengthen policy support, enhance farmers' awareness of green production, and promote increased agricultural productivity and income. Given the decentralized household management and dominant presence of small-scale farmers in main potato production areas, local governments should increase support for green production. This involves fostering enthusiasm for sustainable practices, promoting the adoption of eco-friendly agricultural technologies like organic fertilizers, and assisting farmers in achieving enhanced productivity and income.

(ii) Enhance professional training in green agricultural technology to promote the improvement of quality and efficiency in potato production. Given the positive impact of professional technical training on farmers' adoption of organic fertilizers, the agricultural technology department should intensify training efforts. This can be achieved through comprehensive guidance, including household research, training sessions, distribution of teaching materials, creation of instructional videos, and other effective methods aimed at improving traditional practices and elevating technical efficiency in potato cultivation.

(iii) Enhance the allocation of factor inputs to facilitate the enhancement of cost efficiency for growers. Optimizing the allocation of input factors through field management practices, such as land leveling, formula fertilization, seed mixing, and ridge covering, can improve labor productivity, reduce average production costs, and enhance mechanization levels in potato cultivation. This ensures the optimal allocation of various production factors and elevates growers' cost efficiency levels.

Data availability statement

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

Ethics statement

Ethical approval was not required for the studies involving humans because as the study does not involve any personal data and the respondents were well aware that they could opt out anytime during the data collection phase, no written ethical approval is required. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MZ: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. XX: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation. WN: Writing – review & editing, Formal analysis, Methodology, Validation, Supervision. FZ: Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. AS: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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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