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Achieving more sustainable agricultural production: investigating the impact of agricultural machinery services on fertilizer reduction based on survey data from wheat farmers

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Introduction: Reducing excessive fertilizer use is essential for mitigating environmental harm and achieving sustainable agricultural development. Agricultural machinery services (AMS) are considered a promising means to improve production efficiency and reduce the overuse of inputs. This study investigates the impact of AMS on fertilizer application intensity (FAI) among wheat farmers, aiming to understand whether and how AMS contribute to more sustainable fertilizer use.

Methods: We use survey data collected from 926 wheat farmers across five provinces in the North China Plain. To rigorously identify the effects of AMS on FAI, we employ a combination of linear regression, Least Absolute Shrinkage and Selection Operator (LASSO), two-stage least squares (2SLS), and mediation effect analysis to account for potential confounders and mechanisms.

Results: The empirical analysis reveals three main findings: (1) AMS significantly reduce FAI, and the extent of reduction increases with higher levels of participation in AMS. (2) The FAI-reducing effect of AMS varies substantially across farmers with different socio-economic and farm characteristics. (3) Technological progress and changes in traditional fertilization practices are two key mediating mechanisms through which AMS lower FAI.

Discussion: These findings suggest that promoting AMS can effectively reduce FAI while supporting sustainable agricultural development. Policy efforts should focus on expanding AMS coverage and tailoring services to the needs of diverse farmer groups, thereby facilitating the transition of small-scale farmers toward modern, environmentally friendly production practices.

KEYWORDS

agricultural machinery services, wheat farmers, fertilizer reduction, mechanisms of action, North China Plain

1 Introduction

For a significant period of time, the substantial increase in grain yields in China has been closely associated with the high intensity of fertilizer inputs (Wu et al., 2024). According to data from the Food and Agriculture Organization (FAO), China's grain yields were just 2,791.80 kg/hm^2 in 1978. By 2022, this figure had risen to 6,379.60 kg/hm^2. China is confronted with challenges due to limited arable land per capita and a high population density. The utilization of fertilizers has significantly contributed to ensuring food security. Meanwhile, Fertilizer Application Intensity (FAI) in China has risen rapidly. In 1978, China's FAI stood at 109.27 kg/hm^2. By 1995, it had already surpassed the international environmental safety threshold of 225 kg/hm^2. Furthermore, in 2015, it reached a historical peak of 421.53 kg/hm^2, before declining to 336.24 kg/hm^2 by 2022. The long-term and excessive FAI has given rise to a number of environmental issues (Chen et al., 2017; Shen et al., 2018; Mi et al., 2019). Among them, soil acidity and crusting lead to the deterioration of arable land and a decline in the sustainability of land use (Beerling et al., 2018). As a result, the development of sustainable agriculture is under serious threat (Kotu et al., 2017; Oyetunde-Usman et al., 2021). The Chinese government has consistently emphasized the need to reduce fertilizer use and enhance comprehensive control of agricultural non-point source pollution. However, the current extensive farming practices in China have not been fundamentally altered, and the issue of land pollution remains prominent. The United Nations 2030 Agenda for Sustainable Development sets out Sustainable Development Goals (SDGs), among which SDG12 focuses on responsible consumption and production (López-Fernández et al., 2024). Therefore, in order to maintain a stable supply and demand of agricultural products and ensure food security, China should consider the capacity of environmental resources and expedite the transition toward sustainable agricultural production (Liu et al., 2020).

The "large country, smallholder farmers" model is a typical characteristic of Chinese agriculture (Cui et al., 2018). The rapid growth of secondary and tertiary industries, combined with rising non-agricultural employment and the aging of the rural population, has exacerbated rural labor shortages (Li et al., 2021). This labor shortage poses a major challenge to the modernization of Chinese agriculture. In recent years, agricultural socialization services have emerged as a crucial factor influencing agricultural production. These services have made a noteworthy and substantial contribution to addressing the issues associated with the transformation of small-scale fields into larger ones, as well as fostering a strong connection between small farmers and modern agriculture. Additionally, they have played a significant and beneficial role in promoting fertilizer reduction and ensuring sustainable agricultural production. Agricultural Machinery Services (AMS) refer to the services offered by social and economic organizations or individuals throughout the pre-production, production, and post-production stages of agriculture (Zang et al., 2022). These services essentially represent a form of division of labor within society (Shi et al., 2023; Salam et al., 2021). The Chinese government provides support for the advancement of AMS (Huan et al., 2022). In addition to the long-standing emphasis on agricultural socialization services in the Central Document No. 1, the Ministry of Agriculture and Rural Development's "Guiding Opinions on Accelerating the Development of Agricultural Socialization Services" further highlights the need to modernize and upgrade agriculture through the application of modern science and technology, material equipment, industrial systems, and business forms, due to the large fertilizer usage and low utilization rate in China. There is an urgent need to employ modern science and technology, material equipment, industrial systems, and operational methods to transform and upgrade agriculture. AMS play a vital role in achieving high-quality agriculture and environmentally sustainable agriculture. Driven by market demand and government policies, the development of China's agricultural socialized service system has yielded significant outcomes. By the end of 2023, China had 1.07 million agricultural socialized service organizations, serving over 91 million small-scale farmers and covering 1.97 billion mu of farmland.

Currently, scholars have conducted valuable research on the impact of AMS on fertilizer reduction. First, some scholars have discovered that AMS have a significant influence on both agricultural production and rural households. Scholars have generally reached a consensus regarding the role of AMS in enhancing agricultural production efficiency (Wang et al., 2016; Lu et al., 2019), reducing agricultural production costs (Chen et al., 2022), increasing the income of families, narrowing the income gap and alleviating labor shortages (Liu et al., 2019; Zhang et al., 2017; Cai et al., 2022). Furthermore, contemporary scholars have explored the fertilizer application behavior of farmers and the factors that influence it (Zheng et al., 2022). They have also investigated various approaches to encourage farmers to reduce fertilizer application, such as government support (Smith et al., 2007), organizational models (Zhang M. et al., 2023; Zhang Y. et al., 2023), and cultivated fields area (Bojnec and Latruffe, 2013; Wang et al., 2018). Over time, some scholars have discovered that farmers are not solely responsible for reducing fertilizer use. Their fundamental production strategy is to minimize production risks and maximize yields by increasing fertilizer application. As the division of labor in agricultural production becomes more specialized, there is an increasing trend of outsourcing fertilizer application to service organizations. According to relevant research (Chen and Liu, 2023), AMS have been found to have a significant contribution to reducing fertilizer use. Agricultural socialized service organizations achieve this by adopting advanced production technologies (Huan et al., 2022), creating scientifically-based fertilizer application plans, and improving the precision of field operations (Zhang et al., 2013).

Overall, existing studies largely agree on the positive role of AMS in reducing fertilizer input. However, current research on the impact of AMS on fertilizer input still has certain limitations. The current research, which focuses on the relationship between AMS and FAI, is still in its early stages and lacks a strong theoretical foundation. It is necessary to further enhance the research framework, conduct an in-depth analysis and assessment of the reduction effects of farmers' participation in AMS, and explore the specific mechanisms through which AMS contribute to FAI reduction, as well as the heterogeneous impacts on different farmers.

Wheat, as one of the three major staple crops, plays a vital role in ensuring China's food security and is crucial for achieving sustainable agricultural development. The North China Plain is a major grain-producing region in China and serves as a key area for wheat cultivation. The study investigates how AMS influence environmentally-friendly agricultural practices, drawing on micro-level data from a 2024 survey conducted among 926 wheat farmers in five provinces within the North China Plain. This study aims to address the following research questions. Firstly, whether AMS can prompt wheat farmers to reduce FAI. Secondly, do the effects of AMS on farmers' reduction of FAI vary across different characteristics of household agricultural businesses? Thirdly, what are the underlying mechanisms through which AMS contribute to FAI reduction?

Against the backdrop of intensifying global climate change and resource and environmental constraints, achieving the dual goals of increasing grain production while reducing fertilizer use has emerged as a central issue in sustainable agricultural development. This study aims to examine the impact of AMS on wheat FAI and to explore the mechanisms behind this relationship. Theoretically, it contributes to refining the conceptual framework at the intersection of AMS and non-point source pollution management, providing critical theoretical support for understanding the coordinated development of modern agricultural technology promotion and resource-environment sustainability. Practically, it provides empirical evidence for policymakers to precisely formulate AMS promotion policies and effectively facilitate the green transition of agricultural production, thereby synergistically achieving multiple strategic objectives, including safeguarding national food security, promoting agricultural sustainability, and enhancing the overall quality and efficiency of AMS.

The paper is organized as follows. Section 2 presents the theoretical framework and research hypotheses. Section 3 describes the data sources, model specification, and variable selection. Section 4 presents the empirical results and analysis. Finally, Section 5 summarizes the main findings and offers policy implications.

2 Theoretical analysis and research hypothesis

2.1 Farmers' behavior in the reduction of fertilizer usage and realistic constraints

Farmers, being the primary actors in the context of fertilizer reduction, play a crucial role in determining the effectiveness of such reduction. Farmers' decisions to reduce FAI are influenced by factors such as risk perception, cost-benefit analysis, labor considerations, and technological aspects (Zhang et al., 2017).

Firstly, according to the rational peasant theory, farmers, being rational economic agents seeking to maximize profits, typically prioritize the goal of ensuring survival in their production and operations (Rezaei et al., 2019). They have a tendency to avoid production risks and aim to increase grain output by employing high FAI (Li et al., 2023; Zhou et al., 2024).

Secondly, the logic of FAI reduction should be based on the premise that the marginal cost of adopting FAI reduction behavior by farmers is lower than the marginal benefit. However, meeting this premise is currently challenging. Farmers who adopt FAI reduction technologies often encounter the risk of higher initial input costs, decreased crop yields, and reduced returns in the short term. Although FAI reduction can enhance soil quality and sustainability in the long run, farmers frequently struggle to strike a balance between long-term ecological benefits and short-term economic costs, which results in reservations regarding FAI reduction (Wang et al., 2018).

Thirdly, there is an increasing scarcity of rural labor, which is indicative of a trend toward "low quality, aging, and feminization". Farmers typically rely on the recommendations of agricultural production material retailers, their neighbors, and their own practical experience when it comes to applying fertilizers (Zhang and Hu, 2012). This group has accumulated a wealth of experience in long-standing traditional farming practices. However, they encounter numerous challenges in acquiring and implementing new agricultural technologies, particularly those related to reducing FAI. Modern fertilizer reduction technologies are relatively complex, such as soil testing and precision fertilizer application techniques, which result in higher learning costs for farmers and raise the threshold for adoption.

2.2 The impact of agricultural machinery services on the reduction of fertilizer application

Agricultural machinery service organizations, such as farmers' professional cooperatives and agricultural enterprises, possess advantages in terms of information, technology, and scale that ordinary farmers are unable to match. These organizations are more inclined to adopt sustainable agricultural production methods, which can significantly reduce fertilizers input or improve fertilizer use efficiency (Emmanuel et al., 2016).

Firstly, the informational advantage of AMS organizations plays a vital role in enhancing fertilizer utilization and facilitating sustainable agricultural development. Farmers often lack adequate knowledge and access to information, making it difficult for them to independently determine appropriate FAI (Smith and Siciliano, 2015). On the other hand, AMS organizations are typically equipped with skilled technicians and possess a relative advantage in receiving government training and specialized social training.

Secondly, technological progress is another significant factor. The lack of science and technology is a key reason for excessive FAI by farmers (Xue et al., 2020; Zhang et al., 2016). Even farmers who are willing to apply fertilizer accurately often face financial constraints and operational limitations that prevent them from independently purchasing agricultural green production machinery. In contrast, AMS organizations are able to introduce advanced technology and leverage the positive spillover effect of technology. The organizations have distinct advantages in specialization and greening, and possess a range of advanced agricultural machinery and equipment, such as deep-loosening machines, unmanned plant protection drones, and large-scale straw-returning shredders (Wang et al., 2023). By offering fertilizer application services to farmers at lower prices, they can ensure the uniformity and standardization of fertilizer application operations, enhance the precision of field operations, and reduce the FAI.

Thirdly, scale represents a key advantage. Currently, China's agricultural production is experiencing an aging population and a growing shift toward part-time farming (Liu et al., 2018). Many farmers still rely on traditional, low-efficiency production methods, which weakens their willingness to reduce FAI. Furthermore, there is a lack of capital, technology, and labor, making it difficult to independently implement green production methods. The advantage of scale plays a vital role in lowering production costs. AMS organizations can lower the cost of agricultural machinery application by offering centralized productive services to a large number of farmers (Cao et al., 2024), thus taking advantage of economies of scale and continuous operation. Additionally, these organizations have strong bargaining power in the agricultural market when purchasing green production factors in bulk, which helps alleviate the economic burden on farmers in terms of using

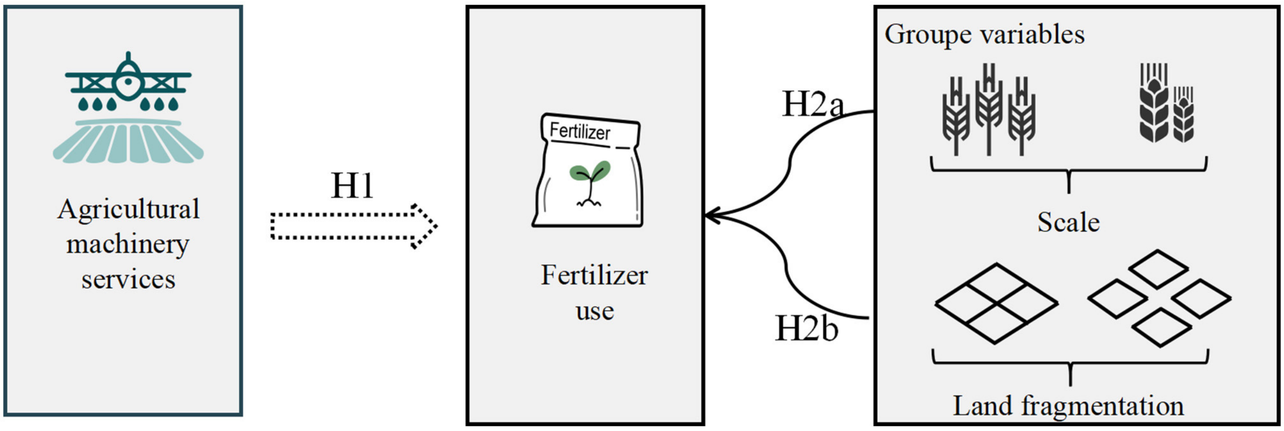

FIGURE 1
Conceptual pathway of AMS promoting FAI reduction.

organic fertilizers and other fertilizer substitutes (Wu et al., 2021). Based on this, we propose Hypothesis 1 (as shown in Figure 1).

Hypothesis 1. AMS is likely to catalyze the reduction of FAI among farmers.

Hypothesis 2a. AMS have a more significant impact on the reduction of FAI by small-scale farmers.

Hypothesis 2b. AMS have a more significant impact on the reduction of FAI by farmers with a high degree of land fragmentation.

2.3 Heterogeneous effects of agricultural machinery services on the reduction of fertilizer application

Farmers' demand for AMS is primarily driven by the need to offset limitations in their own resource endowment. There is a significant level of heterogeneity among farm households, particularly in terms of the resources they possess. Such heterogeneity is reflected in multiple dimensions, including literacy levels, scale of cultivation, number of agricultural laborers, and other individual, household, and production factors (Pierre et al., 2015). It is important to note that farmers with different resource endowments may experience heterogeneous impacts on FAI reduction after participating in AMS. This study aims to analyze the resource endowment of farm households in terms of cultivation scale and fragmentation. Farmers with different cultivation scales exhibit different levels of willingness to invest in agricultural capital. Small-scale farmers, in particular, tend to invest less labor and capital in agricultural production, thus relying more on the support of AMS (Paudel et al., 2019). AMS organizations can effectively reduce the FAI among smaller-scale farmers by providing continuous services at lower prices and with higher quality. Furthermore, it is worth noting that the degree of land fragmentation among ordinary farmers in China is currently high. Large-scale farmers often engage in land consolidation through contracting to reduce fragmentation and streamline land management. However, due to the higher associated costs, large-scale farmers tend to be more cautious than small-scale farmers when making production-related decisions, such as whether to reduce FAI. Based on this, we propose Hypothesis 1 (as shown in Figure 1).

2.4 Analysis of the mechanism of agricultural machinery services on the reduction of fertilizer application

Farmers are the primary stakeholders in the reduction of FAI. The path-dependent nature of farmers' production decisions weakens their intrinsic motivation to reduce FAI. Insufficient technology and knowledge regarding scientific fertilizer application are significant factors contributing to excessive FAI among farmers. AMS have the potential to facilitate FAI reduction by mediating technological progress and catalyzing shifts in traditional fertilizer practices.

2.4.1 Technological progress

According to the theory of technological progress, the optimal allocation of production factors depends on technological progress that is based on the effective substitution of inputs. The amount of fertilizer applied is influenced by factors such as technological progress in agriculture (Hu et al., 2021). Technological progress enables farmers to reduce FAI while maintaining grain yields and sown area. AMS facilitate rational fertilization by integrating green production technologies into farming practices and transforming traditional empirical fertilization methods. Specifically, there are commonly used empirical fertilization methods in agricultural production, such as excessive water and fertilizer application and broadcast application. Transforming these outdated fertilization practices necessitates the introduction of modern production inputs. AMS organizations possess advanced equipment, such as deep loosening machines, unmanned plant protection drones, and large-scale straw returning shredders, and have advantages in promoting green technologies like scientific fertilization and unified prevention and control. AMS organizations utilize induced technological substitution of deep fertilization technology and precision operation tools instead of traditional operation methods to address the non-uniformity and non-standardization issues associated with empirical fertilization. By using specialized mechanized fertilization techniques, they replace traditional production approaches and achieve FAI reduction through improved application methods. Their strong market bargaining power and low procurement costs allow farmers to access and adopt green technologies at reduced expenses. By purchasing AMS, farmers are effectively equipped with the capacity to apply green technologies rapidly and efficiently, enhancing both the adequacy and effectiveness of green input use. Therefore, by purchasing AMS and leveraging the positive spillover effect of technology, farmers can effectively integrate green production factors into their operations, thereby contributing to FAI reduction. Based on this, we propose Hypothesis 3a (as shown in Figure 2).

Hypothesis 3a. AMS prompt farmers to reduce FAI through technological progress.

2.4.2 Shifts in traditional fertilization practices

Compared to AMS organizations, farmers face notable limitations in their fertilizer application decisions. The production characteristics of farmers' empirical and conservative fertilization practices often lead to excessive FAI. The structural transformation of Chinese agriculture, shifting from high-quantity to high-quality fertilization, relies on professional fertilization services.

On the one hand, according to externality theory, reducing FAI can generate positive environmental externalities. These externalities manifest in improved environmental quality and the advancement of sustainable agricultural development, ultimately benefiting society as a whole. However, achieving these positive environmental externalities often comes at the expense of reduced production profits. For example, reducing FAI may temporarily lower crop yields. There exists an imbalance between the costs and benefits associated with reducing FAI. Consequently, farmers may lack the motivation to reduce their reliance on fertilizers (Picazo-Tadeo and Reig-Martínez, 2007). On the other hand, when confronted with poor wheat growth, farmers usually exhibit a phenomenon of "resorting to desperate measures in a panic". Especially in a situation where there are a wide variety of fertilizers with uneven quality, blind fertilization may occur.

When farmers purchase services such as soil-testing-based fertilizer formulation, mechanical fertilization, and full-process trusteeship services, AMS organizations are capable of providing fertilization recommendations or making actual decisions. These organizations employ professional technicians who can promote and popularize new concepts and methods in agricultural production, such as smart technologies and digitalization. By doing so, they guide farmers to adopt modern production methods in crop management (Liu et al., 2019). Additionally, AMS organizations can provide the green production inputs essential for reducing FAI, thereby replacing the rigid dependence on traditional fertilizers and achieving a quantitative and standardized approach to fertilizer application. Based on this, we propose Hypothesis 3b (as shown in Figure 2).

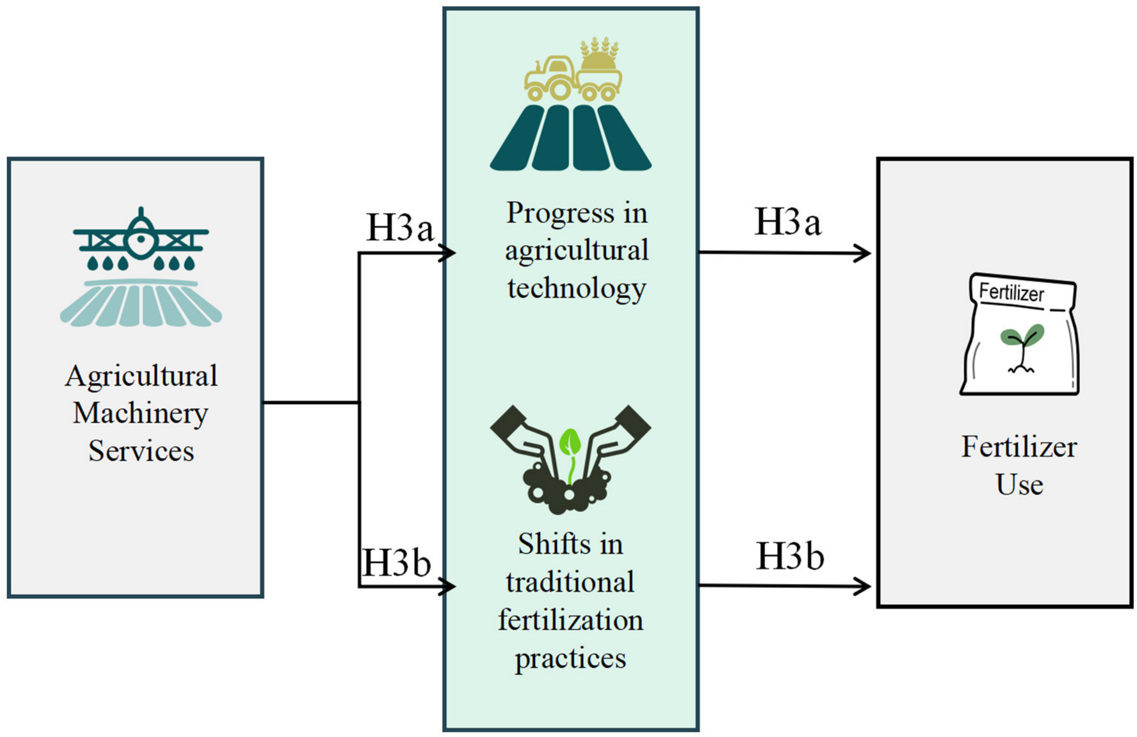

FIGURE 2
Mediating mechanism framework: the role of technological progress and shifts in traditional fertilization practices.

Hypothesis 3b. AMS prompt farmers to reduce FAI through shifts in traditional fertilization practices.

3 Materials and methods

3.1 Data sources

Wheat is one of China's three major staple grains and accounts for approximately one-fifth of the country's total grain consumption. Wheat production is closely tied to national food security and the food consumption of residents. The North China Plain, one of the country's most important grain-producing regions, is known for its highly intensive and large-scale wheat cultivation, accounting for approximately 80% of China's total wheat output. Accordingly, this study focuses on wheat cultivation in the North China Plain, as a representative case for analyzing the impact of AMS on FAI among farmers. Among various agricultural socialized services, AMS represent the most essential and widely adopted component by farmers (Qiu et al., 2023). In this paper, AMS primarily refer to service organizations that provide farmers with production-related technical services to meet the requirements of agricultural production, including land preparation, sowing, fertilization, pesticide application, and harvesting.

The data used in this study were collected through a stratified and random sampling survey of wheat farmers in 59 villages across 35 towns and districts in 14 counties and districts in five provinces—Shandong, Henan, Hebei, Anhui, and Jiangsu—located in the North China Plain. Before conducting the field research, this study systematically gathered multidimensional baseline information including geographic location, economic indicators, grain production data, and demographic information based on the regional characteristics of the five major grain-producing provinces in the North China Plain, and constructed a scientific multi-stage stratified sampling frame accordingly. First, using key indicators such as wheat production, regional economic development level, and the maturity of agricultural service industries, the five provinces—Henan, Shandong, Anhui, Hebei, and Jiangsu—were selected as the primary sampling regions. Second, considering socio-economic factors such as resident population size, per capita GDP and arable land resource endowment, 2–3 prefecture-level cities were selected in each province using typical sampling technique to form the secondary sampling unit. Subsequently, 1–2 representative districts and counties were selected within each sampled city as tertiary sampling units, based on geographic distribution and wheat cultivation scale. Then, based on the gradient of economic development, 1–3 townships were randomly selected within each sampled district or county, followed by the random selection of 1–3 administrative villages in each township. Finally, a systematic random sampling method was employed to select 10–15 regionally representative farming households families in each sample village, ensuring that the sample accurately reflected the fundamental characteristics of the study area.

The survey was carried out by members of the research team from April to August 2024. A face-to-face questionnaire method was employed, and a total of 950 questionnaires were distributed. After removing invalid questionnaires that contained unanswered questions, omissions, and logical inconsistencies, a final sample of 926 valid responses was obtained, yielding a validity rate of 97.47%.

The questionnaire primarily covered the following aspects: (1) Basic characteristics of farmers, such as gender, age, education level, self-rated health status, occupational background, and participation in agricultural technical training; (2) Household characteristics of farmers, which mainly involve understanding the composition of family members. This also includes the number of labor force members, the breakdown of annual household income, and particularly the share attributable to agricultural activities. It also covers participation in cooperatives, the purpose of wheat cultivation, and experience with natural disasters over the past 5 years; (3) Village characteristics, including assessments of topography, the number of households equipped with agricultural machinery, the number of cooperatives, the status of high-standard farmland construction, and other socio-economic indicators; (4) Wheat cultivation management characteristics, covering planting area, cultivation and irrigation conditions, land transfer situation, wheat production costs and revenues, fertilizer and pesticide application, and participation in agricultural machinery services; (5) Farmers' cognitive characteristics, focusing on their perceptions of AMS and the use of fertilizers and pesticides.

3.2 Model construction and research methods

3.2.1 LASSO

This study primarily employs the Least Absolute Shrinkage and Selection Operator (LASSO) regression method to identify the key factors influencing farmers' fertilizer application. Proposed by Robert Tibshirani in 1996, the LASSO regression represents a shrinkage estimation approach. The LASSO algorithm not only addresses the limitations of ordinary least squares and stepwise regression in reaching local optima, but also exhibits superior variable selection capability and effectively mitigates multicollinearity among variables. LASSO regression performs variable selection by introducing an L1-norm penalty term (the sum of the absolute values of the coefficients) into the conventional regression equation. The specific mathematical formulation is as follows:

$$\widehat{\beta}\left(lasso\right) = \arg\overset{2}{\underset{\beta}{\min}} \left\| y - \sum_{j=1}^{k} x_i\beta_i \right\|^2 + \lambda \sum_{j=1}^{k} |\beta_i| \tag{1}$$

In Equation (1): $\arg\min(\boldsymbol{.})$ is a function that seeks the minimum value of a parameter; $\hat{\beta}$ (lasso) is the objective function of minimization $\left\| y - \sum_{j=1}^{k} x_i\beta_i \right\|^2$, is the degree of fitting for the model; $\lambda \sum_{j=1}^{k} |\beta_i|$ is a penalty term, if$\lambda > 0$, the magnitude of its value is directly proportional to the punishment intensity of the model.

When the model contains numerous irrelevant or redundant variables, it tends to become overly complex and susceptible to overfitting the noise present in the training data, thereby impairing its predictive accuracy. LASSO regression eliminates these variables that may lead to overfitting through variable selection, so that the model focuses on the variables that have a true predictive power for the target variable, which can reduce the variance of the model, reduce the overfitting, and thus to some extent reduce the bias of the model.

3.2.2 Construction of the fertilizer input model

To assess the impact of AMS, which is the core explanatory variable, on FAI by farmers, Equation (2) is developed as follows:

$$\ln\left(fert_i\right) = a_0 + a_1 \ln\left(Service_i\right) + \sum\nolimits_{k=1} a_{2k} C_i + \mu_i \tag{2}$$

$\ln\left(fert_i\right)$ represents the logarithmic value of the FAI of the i-th farmer. FAI is measured by the amount of fertilizer applied per mu. $\ln\left(Service_i\right)$ is the logarithmic value of expenditures on AMS. denotes other control variables, including factors such as the personal and family characteristics, agricultural production characteristics, village characteristics, and farmers' cognitive characteristics of the i-th farmer. μ_i is the random error term. In addition, is the intercept term, while and a_2 are parameters to be estimated.

3.2.3 Construction of mediation effect model

To examine the mechanism by which AMS influence FAI and assess whether AMS help reduce FAI by promoting technological progress and shifts in traditional fertilization practices, this study adopts a two-step method to construct a mediation effect model (Jiang, 2022). Specifically, following the estimation of Model (2) and the identification of a significant coefficient indicating the impact of AMS on FAI, model (3) is estimated to explore the influence of AMS on technological progress and shifts in traditional fertilization practices. If model (3) is valid and the coefficient β_1 shows a significant positive relationship, then combined with the preceding theoretical analysis, it can be inferred that technological progress and shifts in traditional fertilization practices mediate the relationship between AMS and FAI.

$$M_i = \beta_0 + \beta_1 \ln\left(Service_i\right) + \beta_2 Z_i + \varepsilon_i \tag{3}$$

Wherein: $\ln\left(Service_i\right)$ it is the core explanatory variable, represented by the per mu service expenditure cost; $M_i$is the mediating variable; $Z_i$is the control variable affecting fertilizer input; β_0, β_1 and β_2 are parameters to be estimated; and ε_i is the random error term.

3.3 Variable selection and descriptive statistics

3.3.1 Variable selection

The primary objective of this paper is to empirically assess whether AMS can contribute to the reduction of FAI. The definitions and descriptions of the key variables are presented in Table 1.

(1) Dependent variable. The dependent variable in this study is FAI, measured by the actual amount of fertilizer applied per mu (kilograms/mu) in wheat production. Due to the presence of zero values for this variable in the sample, the analysis used average fertilizer application per mu + 1 to take the logarithm to reduce identification bias due to large differences in the data.

(2) Core explanatory variable. With regard to the measurement of AMS, the main indicators used in micro studies include whether or not to purchase AMS, the number of service segments purchased, and total expenditure on these services. Given that farmers typically maintain clear mental records of service costs and can provide reliable data, this study adopts the average cost of AMS per mu (yuan/mu) as the core explanatory variable. Due to some farmers report zero expenditure, the empirical analysis applies a natural logarithm transformation to (AMS expenditure + 1) to address zero values.

(3) Mediating variables. This study identifies the level of technological progress and the shifts in traditional fertilization practices as mediating variables. Specifically, the technological progress variable is measured by "the extent of adoption of mechanical fertilization, soil-based fertilizer application, and straw return technology," following the approach of Cao et al. (2022). The shifts in traditional fertilization practices are reflected in the extent to which farmers' fertilization practices are influenced by service organizations, either through direct fertilization or guidance.

(4) Control variables. The determinants of farmers' fertilizer application behavior are multifaceted. The decision-making process for fertilization by farmers is influenced by various internal and external factors, including the head of the household, family dynamics, land characteristics, and regional factors. Based on previous theoretical analysis and existing research, this paper considers factors such as the characteristics of agricultural decision-makers, family characteristics, agricultural production characteristics, farmers' cognitive characteristics, and external environmental factors. Among these factors, the head of the household plays a crucial role as the primary decision-maker in agricultural production. Their subjective and objective individual characteristics, such as production experience, labor allocation, and subjective cognition (including education level, participation in agricultural technology training, part-time employment, and knowledge of fertilization), directly influence fertilization decisions. The family unit serves as the fundamental entity in agricultural production. Family characteristics, such as the ability of the labor force to respond to emergencies during busy farming seasons and the availability of productive assets, indirectly affect fertilization decisions through labor and capital endowments, respectively. Land serves as the medium for fertilizer application, and its characteristics directly determine the demand for fertilizers. Planting scale, degree of land fragmentation, whether it is high-standard farmland, and land contract rent collectively provide a comprehensive reflection of land characteristics, considering both land quantity and land quality. External

TABLE 1 The description of the variables.

Variable	Definition (unit)	Mean	Standard deviation
Dependent variable			
FAI	Fertilizer application rate per mu (kg/mu)	71.593	24.346
Core explanatory variable			
Agricultural machinery service	Agricultural machinery service costs per mu (yuan/mu)	137.649	106.625
Mediating variables			
Technological progress	number of adoptions of mechanical fertilization, soil testing and formula fertilization, and straw return to field technology (units)	1.549	0.837
Shifts in traditional fertilization practices	Use of agricultural machinery service organizations for fertilization or guidance in fertilization: 1 if yes, 0 if no	0.109	0.312
Control variables			
Characteristics of agricultural production decision-makers			
Head of household gender	Gender: 1 if male, 0 if female	0.719	0.450
Head of household's village Official Status	Head of household as village official: 1 if yes, 0 if no	0.073	0.261
Household head's education level	Educational attainment of the household head (years)	9.136	3.754
Household head's part-time employment	Household head's part-time employment: 1 if yes, 0 if no	0.482	0.500
Household characteristics			
Labor force burden coefficient	Non-labor force population to labor force population ratio	1.256	1.178
Status of productive assets	Original value of agricultural machinery purchased (yuan)	74,802.740	284,456.900
Production characteristics			
Scale of wheat cultivation	Actual wheat cultivation area (mu)	84.092	213.019
Land fragmentation	Average plot size (mu)	17.987	93.190
Land quality	Is the land quality good? 1 if yes, 0 if no	0.933	0.250
Land contract rent	Actual land contract rent (yuan/mu)	213.013	350.875
Village characteristics			
Village topography	Is the area a plain? 1 if yes, 0 if no	0.943	0.232
Number of village cooperatives	Number of active village cooperatives (units)	1.141	1.875
Proportion of village-scale operation	Cultivation scale of large grain producers and cooperatives/village land scale	27.870	28.016
Farmers' cognitive characteristics			
Government technical guidance	Do you find government training to be instructive for your actual agricultural production? 1 = Strongly Disagree; 2 = Disagree; 3 = Uncertain; 4 = Agree; 5 = Strongly Agree	3.570	1.074
Internet utilization ability	Do you usually use the internet to search for information? 1 = Strongly Disagree; 2 = Disagree; 3 = Uncertain; 4 = Agree; 5 = Strongly Agree	2.416	1.296
Cognition of fertilizer reduction services	Do you believe that agricultural machinery services can help reduce the intensity of fertilizer application? 1 = Strongly Disagree; 2 = Disagree; 3 = Uncertain; 4 = Agree; 5 = Strongly Agree	3.260	0.897
Cognition of yield increase services	Do you believe that agricultural machinery services contribute to increased crop yields? 1 = Strongly Disagree; 2 = Disagree; 3 = Uncertain; 4 = Agree; 5 = Strongly Agree	3.361	0.907
Cognition of fertilizer application	Do you agree that excessive use of fertilizers leads to environmental pollution? 1 = Strongly Disagree; 2 = Disagree; 3 = Uncertain; 4 = Agree; 5 = Strongly Agree	3.382	1.228
Instrumental variable			
Number of agricultural machinery households in the village	Actual number of agricultural machinery households in the village (units)	4.826	4.786

1 mu = 1/15 ha.

characteristics, such as village topography, the number of cooperatives in the village, and the proportion of village-scale operations, are also important factors that influence farmers' decisions regarding the quantity of fertilization.

This study selects 19 potential variables influencing farmers' FAI, and uses LASSO regression method to perform variable selection and parameter estimation. This method is particularly effective in addressing multicollinearity issues within the model. Variable selection is conducted based on the Extended Bayesian Information Criterion (EBIC). As the penalty coefficient increases, variables are sequentially included in the model. When the value of λ is 0.0286, the model selects 12 variables, namely AMS cost, education level of the head of household, number of village cooperatives, degree of village scale operation, degree of farmland suitability for machinery, land contract rent, farmers' fertilization cognition, etc.

3.3.2 Sample characteristics

Table 1 presents the descriptive statistical findings for the core variables. The results show that the average amount of fertilizer applied per unit of land by the sampled farmers is 71.59 kg per mu, which significantly exceeds the upper limit of 30 kg per mu recommended by developed countries (Du and Lai, 2023). It is important to highlight that the FAI among the sampled farmers is relatively consistent with the findings of scholars such as Gao et al. (2023), indicating the reliability of the survey data.

In terms of the characteristics of decision-makers in agricultural production, the majority of current rural household heads are male. The average education level is 9.136 years, and nearly 52% of household heads are engage in part-time jobs, indicating a current trend of "low educational attainment and part-time employment" among the rural labor force. At the family characteristic level, only 27% of farmers have purchased large agricultural machinery and equipment, such as tractors and harvesters. The average labor burden coefficient is 1.256. In terms of agricultural production characteristics, the average wheat cultivation area of the sampled farmers is 84.092 mu, and 81.32% of farmers have a cultivation area smaller than the average value. The average plot size of the sampled farmers is 17.987 mu, and 88% of farmers have an average plot size smaller than this value. The relatively large average cultivation area and plot size can be attributed to the rapid development of the secondary and tertiary sectors in Jiangsu Province, which has led to sufficient non-agricultural employment opportunities, a high land transfer rate, and a higher proportion of large-scale agricultural entities compared to other provinces. The land quality of the sampled farmers is relatively good, with approximately 93% reporting suitable conditions for mechanized operations. The average land contract rent is 213.013 yuan, and the rent in Shandong Province and Henan Province is relatively high. Regarding external environmental characteristic level, the area is mainly plain. On average, each village has 1.141 cooperatives, and the average proportion of village scale operation is 27.87%. In terms of farmers' cognitive characteristics, the study uses a 5-point Likert scale to measure relevant perceptions. It is found that farmers' cognitions of government technical guidance, the yield-increasing and weight-reducing benefits of AMS, and FAI are all at a relatively low level, within the range of 3.2–3.6.

4 Results

4.1 Benchmark regression

This paper constructs a regression model to examine the impact of AMS on FAI. The regression results are shown in Table 2. Model 1 includes only the core explanatory variable. To ensure the reliability of the AMS coefficient estimates, model 2 includes additional control variables. The estimation results of Model 1 and Model 2 indicate that the coefficient of AMS is significantly negative at the 1% level. This suggests that the AMS does contribute to the reduction of FAI. This finding offers a novel perspective on the reduction of fertilizer use in Chinese agriculture and confirms Hypothesis 1. Our results are consistent with Xia and Cui (2023) and Huang et al. (2024) who also found the reduction in fertilizer use under agricultural services in China. However, Emmanuel et al. (2016) found that access to extension services significantly promotes adoption of fertilizer in sub-Saharan Africa. These differences are likely rooted in fundamental disparities in agricultural development stages, as China has achieved a high level of agricultural modernization with well-established commercialized farming systems that focused, on optimizing input use efficiency. In contrast, agriculture in Africa, constrained by climate challenges and underdeveloped infrastructure, remains at

TABLE 2 Estimation results of the impact of AMS on FAI.

Variable	FAI	
	(1)	(2)
AMS	−0.021*** (0.005)	−0.015*** (0.006)
Household head's education level		−0.008** (0.004)
Status of productive assets		0.051 (0.030)
Scale of wheat cultivation		−0.001 (0.012)
Land fragmentation		0.010 (0.013)
Land quality		−0.133*** (0.036)
Land contract rent		0.001 (0.001)
Village topography		−0.071 (0050)
Number of village cooperatives		−0.016** (0.007)
Proportion of village-scale operation		−0.004*** (0.001)
Cognition of yield increase services		−0.034*** (0.012)
Cognition of fertilizer application		−0.068*** (0.025)
Constant	4.982*** (0.023)	5.615*** (0.105)
Number of observations	926	926
R-squared	0.016	0.145
Prob > *F*	0.000	0.000

*, ** and *** denote significance at 0.10, 0.05, and 0.01, respectively. Robust standard errors are in parentheses.

a stage of yield intensification. In this context, extension services primarily aim to promote the adoption of basic inputs to address persistent under application. This divergence in development stages results in differing outcomes in input usage.

With regard to individual and household characteristics, the education level of the household head shows a significant negative association with FAI in wheat. Specifically, each additional year of education is associated with an average 0.8% decrease in FAI, statistically significant at the 1% level. The education level of the household head is indicative of their knowledge and technical cognitive ability, and a higher education level is more favorable for achieving reduced fertilizer production.

With regard to production characteristics, high quality agricultural land holds great significance in reducing FAI. This can be ascribed to the elevated level of agricultural mechanization subsequent to land remediation, the enhancements in irrigation and drainage systems, and the construction of field roads. These factors help improve fertilizer use efficiency and reduce dependence on fertilizers. However, the impact of farmland cultivation area on FAI is not statistically significant, although the correlation was negative. The study found that due to high land rental cost, farmers who grow on a larger scale usually prioritize maximizing grain production and tend to overlook environmentally friendly and sustainable agricultural practices.

With regard to village characteristics, a significant negative correlation is observed between the number of cooperatives in a village and the FAI. At the significance level of 1%, a 1% increase in the number of cooperatives corresponds to a 1.6% decrease in FAI. Additionally, a significant negative correlation exists between the proportion of village-scale operations and FAI. At the 1% significance level, a 1% increase in the proportion of village-scale operations leads to a 0.4% reduction in FAI. The number of village cooperatives and the extent of large-scale operations can partially indicate the level of organization among farm households, which is an important reflection of agricultural modernization. New agricultural management entities, such as cooperatives and large-scale grain farmers, typically offer specialized technical services and guidance, along with timely dissemination of new agricultural technologies and management practices. As a result, farmers are better able to respond to government initiatives aimed at reducing fertilizer use.

With regard to farmers' cognitive characteristics, their perception of AMS is found to have a significantly negative effect on FAI at the 1% significance level. Similarly, farmers' perception of fertilizer application also has a negative effect on FAI at the 1% significance level. The more accurate the farmers' understanding of AMS and fertilizer application, the greater the reduction in their FAI. Empirical evidence suggests that farmers often hold cognitive misconceptions regarding fertilizer application, mistakenly believing that higher fertilizer application leads to increased crop yield.

4.2 Discussion on endogeneity

The issue of endogeneity poses a significant challenge when examining the behavioral decisions of farmers and their subsequent impacts (Khonje et al., 2018). In the preceding section examined the relationship between AMS and FAI among farm households. The analysis revealed that AMS significantly reduced FAI among farm households. Nevertheless, it is important to investigate the robustness of this finding in light of potential endogeneity concerns. Therefore, further empirical investigation is warranted.

Firstly, reverse causality may present. A decrease in FAI could drive farmers to seek AMS, as those applying less fertilizer may be more inclined to adopt such services to access advanced agricultural technologies.

Secondly, omitted variable bias poses another challenge. Given that the behavior of farmers in reducing FAI is influenced by a multitude of factors, it becomes challenging to incorporate all these factors into the model. Consequently, the exclusion of certain variables may have a significant impact on the research findings. Moreover, some variables that influence FAI reduction behavior are inherently difficult to quantify, further complicating the estimation process.

Thirdly, self-selection bias must be considered. Farmers' decisions to adopt AMS are influenced not only by observable characteristics, such as the years of education of the decision-makers, but also by unobservable factors, such as managerial skills. For instance, farmers with higher managerial skills are more likely to adopt AMS and to apply fertilizers in a more scientific and systematic manner. Consequently, estimates obtained through Ordinary Least Squares (OLS) method may overstate the true impact of AMS on FAI reduction.

Identifying an appropriate instrumental variable for the core explanatory variable is a well-established approach to addressing endogeneity issues (Wooldridge, 2015). To address potential endogeneity, this study first identifies a valid instrumental variable. An appropriate instrumental variable must generally satisfy three criteria: (1) it must be highly correlated with the endogenous variable; (2) it should be exogenous in the equation, unrelated to the error term; (3) the number of instrumental variables should be equal to or greater than the number of endogenous variables. Accordingly, the paper conducts a correlation analysis to identify instrumental variables that are highly related to the cost of agricultural machinery services, followed by a two-stage least squares (2SLS) regression.

Previous studies have employed different instrumental variables such as the adoption rate of AMS among village households (Zhang M. et al., 2023; Zhang Y. et al., 2023), village terrain (Zhang et al., 2022), and the highest level of education among family members (Guo et al., 2020; Xia and Cui, 2023) to empirically test the causal effect of AMS on FAI. Drawing on related studies, this paper selects the number of agricultural machinery households in a village as an instrumental variable for AMS. On the one hand, the number of agricultural machinery households in a village significantly affects the adoption of AMS by farmers, thereby satisfying the relevance requirement for an instrumental variable. On the other hand, it does not directly impact the FAI of farmers, thus satisfying the exogeneity requirement for an instrumental variable.

Table 3 presents the regression results from the instrumental variable approach. The first-stage regression results reveal that the

TABLE 3 IV-2SLS estimation results.

Variable	First stage		Second stage	
AMS			−0.137**	(0.054)
IV	0.058***	(0.021)		
Constant	2.903***	(0.651)	5.992***	(0.219)
Controls	Yes		Yes	
Number of observations	926			
Kleibergen–Paap rk LM statistic	9.913***			
F-value	14.060			

*, ** and *** denote significance at 0.10, 0.05, and 0.01, respectively. Robust standard errors are in parentheses.

instrumental variable is significantly and positively associated with the potential endogenous variable at the 1% significance level. Moreover, the *p*-value for the Kleibergen–Paap rk LM statistic is <0.01, indicating that the instrumental variable meets the relevance condition. The first-stage F-statistic is 14.060, which exceeds the critical value for the Cragg–Donald Wald statistic, thereby suggesting that there is no issue of weak instruments.

Moreover, the first-stage regression demonstrates a significant positive effect of the instrumental variable on AMS. This finding reinforces the strong correlation between the instrumental variable and AMS, indicating that villages with a higher number of agricultural machinery households are more likely to adopt AMS. In the second stage, the regression coefficient for AMS is −0.137, and is statistically significant at the 5% level. This result is consistent with the sign and significance level observed in the baseline regression results. Therefore, even after accounting for potential endogeneity issues, AMS continue to exhibit significantly negative impact on FAI, thereby lending further support to Hypothesis 1.

4.3 Robustness tests

To assess the robustness of the baseline regression results, this study follows existing research and performs robustness tests through tail trimming, reducing the sample size, and replacing the dependent variable. First, to account for potential outliers, this study trims the top and bottom 5% of the relevant variables to construct Model 3. Second, the sample is modified by randomly removing 10% of the data from each province, resulting in Model 4 with a reduced sample size. Third, Model 5 replaces the proxy variable for FAI, which is the amount of fertilizer applied per mu, with the cost of fertilizer applied per mu. A comparison of the robustness test results in Table 4 with the baseline regression shows that the regression coefficients for AMS are negative and statistically significant at the 5% level across all three models. This further confirms the importance of AMS in reducing FAI. Additionally, the results for the control variables are generally consistent, although they are not included here due to space constraints. In conclusion, the robustness test results demonstrate the reliability and consistency of the previous findings.

TABLE 4 Robustness test estimation results.

Variable	(3)	(4)	(5)
AMS	−0.014*** (0.005)	−0.013*** (0.006)	−0.014** (0.006)
Controls	Yes	Yes	Yes
Constant	5.582***	5.624***	6.163***
Number of observations	926	833	926
R^2	0.181	0.143	0.094

*, ** and *** denote significance at 0.10, 0.05, and 0.01, respectively. Robust standard errors are in parentheses.

4.4 Group difference analysis

Previous analysis has confirmed that AMS have a significant negative impact on FAI. However, heterogeneity among different groups of farmers may affect the robustness of the findings. Therefore, this paper takes into account the actual situation of agricultural production and divides the sample farmers into large-scale and small-scale farmers, based on whether their cultivation area is greater than the sample average. Furthermore, farmers are further categorized as either concentrated or dispersed landholding, based on whether their plot size is greater than the sample average. Models 6 to 9 are then constructed to examine the impact of AMS on FAI under different planting conditions. The regression results of the group difference analysis are presented in Table 5.

The findings indicate that for farmers with small cultivation scales and dispersed landholdings, the coefficients for AMS are negative and statistically significant at the 1% and 5% levels, respectively. This suggests that AMS have a significant negative impact on FAI for farmers with these characteristics. In other words, farmers with smaller-scale and more dispersed landholdings are more likely to reduce fertilizer use when adopting AMS.

Based on the research, this paper offers the following explanations for the above conclusions. First, large-scale farmers, in order to reduce production costs and decrease the difficulty of land maintenance, often consolidate their cultivated land through land exchange or similar methods to achieve contiguous plots. As a result, there is a significant similarity between large-scale farmers and concentrated landholding farmers, as well as between small-scale farmers and dispersed landholding farmers, leading to similar conclusions. Second, large-scale farmers typically specialized in agricultural production, with a high rate of agricultural machinery equipment and strong autonomy and independent decision-making in agricultural production. Their adoption of AMS, in terms of both breadth and depth, is relatively lower compared to small farmers, and thus they are less influenced by these services. Third, since agricultural income accounts for a high proportion of total household income among large-scale farmers, they are more sensitive to the risks of yield and profit loss associated with fertilizer reduction. As a result, they tend to adopt a more cautious attitude to reducing FAI. Based on the above analysis, the adoption of AMS is more beneficial for small-scale and dispersed landholding farmers to reduce their FAI. These findings lend support to research hypotheses 2a and 2b.

TABLE 5 Regression results of group differences.

Variable	Cultivation area		Plot size	
	Large-scale (6)	Small-scale (7)	Concentrated (8)	Dispersed (9)
AMS	−0.010 (0.010)	−0.018*** (0.007)	−0.017 (0.014)	−0.016** (0.006)
Controls	Yes	Yes	Yes	Yes
Constant	5.798***	5.592***	6.157***	5.590***
Number of observations	173	753	111	815
R^2	0.126	0.161	0.177	0.147

*, ** and *** denote significance at 0.10, 0.05, and 0.01, respectively. Robust standard errors are in parentheses.

TABLE 6 Regression results of mechanism analysis.

Variable	Technological progress (10)	Shifts in traditional practices (11)
AMS	0.045*** (0.013)	0.035*** (0.004)
Technological progress	–	–
Shifts in traditional practices	–	–
Controls	Yes	Yes
Constant	0.259***	−0.313***
Number of observations	926	926
R^2	0.181	0.104

*, ** and *** denote significance at 0.10, 0.05, and 0.01, respectively. Robust standard errors are in parentheses.

4.5 Mechanism analysis

Building on the theoretical analysis, AMS mainly influence FAI by farmers through two mechanisms: promoting technological progress and shifts in traditional fertilization practices. Following the approach of Cao et al. (2022), the first mediating variable technological progress, is measured by farmers' adoption of three technologies: mechanical fertilization, soil testing and formula fertilization, and straw return to fields. The second mediating variable is shifts in traditional fertilization practices, primarily assessing whether fertilization decisions are made by service organizations or guided by them. After confirming that AMS have a significant impact on FAI, a two-step method is utilized to examine the mediating roles of technological progress and shifts in traditional fertilization practices in this relationship. The regression results, based on data substituted into Model (2), are presented in Table 6.

Model 10 shows that the coefficient for the impact of AMS on technological progress is positive and statistically significant at the 1% level. This indicates that AMS have promoted technological progress. As theoretically discussed earlier, technological progress directly facilitate the reduction of FAI. Therefore, according to the two-step method for testing mediating effects, it is evident that technological progress plays a mediating role in the relationship between AMS and FAI reduction, confirming the mediating pathway "agricultural machinery services → Technological Progress → Fertilizer Reduction." Hypothesis H3a is thus supported.

Model 11 shows that the coefficient for the impact of AMS on shifts in traditional fertilization practices is positive and statistically significant at the 1% level. This indicates that AMS have facilitated shifts in traditional fertilization practices. As previously analyzed theoretically, the shifts in traditional fertilization practices directly promote the reduction of FAI. Therefore, based on the two-step method for testing mediating effects, it is demonstrated that shifts in traditional fertilization practices plays a mediating role in the relationship between AMS and FAI reduction, confirming the mediating pathway "agricultural machinery services → Shifts in Traditional Fertilization Practices → Fertilizer Reduction." Hypothesis H3b is thus supported.

5 Research conclusions and policy recommendations

This study evaluates the impact of AMS on the reduction of FAI among wheat farmers in the North China Plain, based on a micro-level dataset of 926 households. Employing a series of econometric models—including OLS, LASSO regression for variable selection, instrumental variable estimation to address potential endogeneity, and mediation analysis—we provide empirical evidence on how AMS influence FAI at the household level.

The results consistently show that AMS are significantly associated with the reduction in FAI. This negative relationship remains robust across multiple specifications, including alternative samples, variable definitions, and the correction for endogeneity bias. Our findings indicate that enhanced access to such services can serve as an effective pathway to promote green agricultural practices, particularly in the context of smallholder-dominated farming systems.

Further analysis reveals heterogeneity in the effects across different types of farmers: those with smaller cultivation scales and higher land fragmentation benefit more from AMS in terms of FAI reduction. Mediation analysis shows that two distinct mechanisms—technological progress and shifts in traditional fertilization practices—explain the service effect. On one hand, AMS improve the efficiency of fertilizer use by introducing precision fertilization and standardized practices. On the other hand, AMS reduce the influence of outdated fertilization habits by shifting key decision roles from farmers to professional service providers. Together, these findings underscore the potential of AMS to align productivity enhancement with environmental sustainability objectives in China's agricultural sector.

This study provides valuable insights for policymakers in the agricultural sector.

The findings of this study highlight the significant role of AMS in promoting FAI reduction among smallholder farmers. In light of this, policymakers should focus on expanding the coverage and availability of AMS across rural areas. By scaling up service supply networks and reducing service costs through financial subsidies or equipment-sharing mechanisms, governments can enhance the accessibility of such services. This will provide the institutional foundation for facilitating green input practices on a larger scale.

Second, efforts to promote AMS should be tailored to specific farmer profiles. Our analysis reveals that the fertilizer-reducing effects of AMS are more pronounced among farmers with lower education levels, smaller cultivation scales, and higher land fragmentation. These groups typically face higher barriers to adopting precision technologies on their own and thus benefit disproportionately from external service interventions. Targeted outreach programs, customized service packages, and location-specific subsidies can ensure that service expansion reaches the most responsive populations.

Third, enhancing the effectiveness of AMS requires complementary strategies that address the underlying mechanisms of change. As mediation analysis suggests, AMS reduce FAI not only by introducing technological progress, but also by reshaping traditional fertilization practices. Policies should therefore support technology diffusion—such as soil testing and precision fertilization tools—while also promoting behavioral change through farmer training, decision support tools, and integrated extension systems.

In summary, AMS, when combined with inclusive targeting and complementary knowledge interventions, represent a scalable and impactful approach to aligning smallholder productivity with environmental sustainability objectives. These insights can inform future rural development strategies and fertilizer management policies in China and other developing economies.

Data availability statement

The data from this study is not available for public use because it contains private information about individuals. However, the study provides comprehensive details regarding its research methods and statistical analyses, which can be utilized by other researchers to reproduce the findings in a similar manner. Requests to access the datasets should be directed to the the corresponding author.

Author contributions

CL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. WG: Conceptualization, Supervision, Writing – review & editing. LX: Conceptualization, Funding acquisition, Supervision, 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.

Generative AI statement

The author (s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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