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Agricultural Productive Services, Stage-Specific Technical Efficiency, and Sustainable Rice-Based Food Systems: Evidence from Jiangsu, China

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Abstract

Achieving sustainable rice production is essential for food security, rural livelihoods, and the resilience of rice-based food systems that supply raw materials to the food processing industry. Improving technical efficiency (TE) at the farm level is a key pathway to reduce resource use and environmental pressures per unit of output while ensuring a stable supply of high-quality rice for downstream processing and value-added products. Drawing on micro-survey data collected in 2021–2022 from 455 rice farmers selected through a multi-stage sampling strategy in Jiangsu Province, China, this study investigates how agricultural productive services (APSs) affect stage-specific technical efficiency along the production process and discusses the implications for sustainable rice production and the rice-based food industry. We apply a stochastic frontier production function to estimate overall and stage-specific TE and examine the effects of different APS combinations for land preparation, sowing, fertilization, pest control, and harvesting. The results show that overall participation in APSs significantly improves rice farmers' TE. Stage-specific analysis reveals that APSs in land preparation, sowing, and harvesting are associated with higher TE, supporting more sustainable use of machinery and labor, while APSs for fertilization and pesticide application do not consistently improve TE and may reflect potential overuse of chemical inputs. Multi-stage service combinations that include both production and pest-control operations can further enhance TE. These findings suggest that well-designed APSs can contribute to sustainable intensification and low-carbon transformation of rice production, thereby strengthening the sustainability of rice-based food systems. Policy interventions should guide APS providers and farmers toward integrated, precision-oriented, and environmentally friendly service packages that support both farm-level efficiency and the sustainability goals of the broader food industry.



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1. Introduction

Rice is one of the most important staple grains in China, playing a central role in national food security and rural livelihoods. At the same time, rice-based food systems are increasingly recognized as critical to achieving the Sustainable Development Goals, as they link primary production to a wide range of processing, distribution and consumption

activities. Rice is both a staple food and a key raw material for the food processing industry, while rice cultivation is also an important source of agricultural greenhouse gas emissions and other environmental pressures. Improving farm-level technical efficiency in rice production is therefore a crucial pathway to increasing food availability per unit of land and input use, and can, in principle, support higher output without proportionately intensifying input use or exacerbating environmental degradation, provided that efficiency gains are not offset by expansion in total cultivated area or input intensity [1,2]. Recent work developing sustainability indicators for rice and wheat supply chains underscores that upstream resource-use efficiency and the quality and stability of raw material supply are critical determinants of environmental and socio-economic performance at subsequent processing, storage, packaging and distribution stages [3]. In this study, the connection between farm-level rice production and the food industry is indirect and operates through the efficiency, quality and stability of rice supplied as a key raw material; improvements in technical efficiency and resource-use efficiency upstream support more sustainable and resilient rice-based food systems and processing activities.

In recent years, rice production in China has faced a series of structural challenges, including rising production costs, labor shortages caused by rural out-migration, ageing farmers and increasing uncertainty in grain prices. For example, real on-farm labor costs in Chinese agriculture increased by about 8% per year between 1997 and 2010 [4], and the number of rural migrant workers reached 292.51 million in 2021, up 2.4% from the previous year [5], indicating sustained out-migration of rural labor. The main entities involved in rice production include not only small-scale rice farmers, but also family farms, large-scale growers and professional farmer cooperatives, along with other new types of operating entities. Small-scale farmers often struggle with fragmented land management, outdated equipment, limited access to specialized labor, low levels of production specialization and fragmented operations, resulting in relatively low rice production efficiency. New operational entities encounter obstacles in scaling land transfers due to rising land rental costs, depressed grain prices and uncertainties regarding rental periods, which together hinder improvements in rice production [6–9].

To address these constraints, China has vigorously promoted agricultural productive services (APSs), such as mechanization services, outsourced operations for specific production links and integrated service packages [10–12]. As early as Postner and Gilfix [13], APSs were viewed as a product of labor division that can significantly reduce production costs and enhance the benefits of large-scale agricultural production. Subsequent empirical studies for China show that mechanization and outsourcing services substitute machinery for human and animal labor, reduce transaction costs in factor markets and help connect smallholders to larger downstream markets [4,14]. Recent work developing sustainability indicators for rice and wheat supply chains underscores that upstream resource-use efficiency, quality and stability of raw material supply are critical determinants of environmental and socio-economic performance at subsequent processing, storage, packaging and distribution stages [3]. In this study, the connection between farm-level rice production and the food industry is indirect and operates through the efficiency, quality and stability of rice supplied as a key raw material; improvements in technical efficiency and resource-use efficiency upstream support more sustainable and resilient rice-based food systems and processing activities.

Agricultural productive services also play a crucial role in advancing modern agriculture and reshaping agricultural development approaches. By enabling specialization in certain production stages and encouraging adoption of improved technologies, APSs can accelerate adjustments in the agricultural industrial structure and offer potential solutions to the current issues in China regarding “who will farm” and “how farming will

be done” [10,11]. In the Chinese context, studies have documented that mechanization services and outsourcing not only help grain producers cope with labor shortages but can also change the optimal farm size and the relationship between scale and efficiency [6,9,15]. Moreover, the development of service markets interacts with farmers’ non-farm employment decisions and land rental behavior, altering the effective allocation of labor and land in rural areas [7,8,16].

Whether APSs enhance technical efficiency, however, remains an open empirical question. A first strand of research explicitly estimates technical efficiency using frontier methods. These studies often employ stochastic frontier analysis or data envelopment analysis to examine how APSs or related factors affect TE. For example, Chen et al. [17], He et al. [10], Qing et al. [15], Yan et al. [9] and Ji et al. [18] used farm-level frontiers to show that access to services, credit or modern technologies can reduce technical inefficiency, although the magnitude and direction of effects differ by context and service type. In the context of low-carbon agriculture, Geng et al. [12] also analyzed the relationship between APSs and efficiency as part of a broader assessment of green transformation.

A second strand focuses primarily on productivity or cost outcomes, rather than on technical efficiency per se. Tang et al. [19], for example, examined how production services affect the cost of rice farming and found that services can significantly reduce production costs. Chen et al. [20] analyzed the role of outsourcing in improving production efficiency within a meso-level analysis framework, while Wang et al. [4] showed how rising wages and mechanization drive substitution between capital and labor in Chinese agriculture. These studies underscore that APSs and mechanization influence farm productivity and cost structures, even when technical efficiency is not modeled explicitly as a frontier-based measure.

Taken together, previous studies reveal no consensus on how APSs affect technical efficiency. This lack of consensus appears to stem from heterogeneity across production links and stages, differences in the quality and content of services, and variation in producer types and organizational forms. However, relatively few studies jointly distinguish APSs by production stage, service combinations and producer type within a unified analytical framework, particularly in rice-based systems.

Existing research further suggests that different types of APSs have heterogeneous effects on technical efficiency. Some scholars argue that labor-intensive services have a positive impact on technical efficiency because they can effectively substitute for on-farm labor, reduce production costs and increase agricultural output [18]. In contrast, technology-intensive services can be difficult to standardize and monitor, and their performance is heavily influenced by human factors during the service process. These features make the quality of service provision less transparent and can generate adverse impacts on technical efficiency when monitoring is imperfect [21]. Another line of research finds the opposite pattern: services that rely on technology or capital—such as mechanization services or integrated outsourced operations—can significantly enhance technical efficiency, while routine labor-intensive services exert relatively small effects [6,15,19,22]. Taken together, previous studies reveal no consensus on how APSs affect technical efficiency. This lack of consensus appears to stem from heterogeneity across production links and stages, differences in the quality and content of services, and variation in producer types and organizational forms. However, relatively few studies jointly distinguish APSs by production stage, service combinations and producer type within a unified analytical framework, particularly in rice-based systems.

At the same time, recent research on sustainable food processing and food-industry systems has emphasized the importance of valorizing agro-food wastes, developing circular-economy strategies and designing sustainable packaging solutions [23–25]. For example,

agro-food wastes from the olive mill and sugar industry can be transformed into novel adsorptive materials [23], shrimp-processing waste can be valorized into novel foods with potential health benefits [24] and olive oil mill by-products can be used to produce sustainable antimicrobial food-packaging films [25]. These studies highlight the potential for downstream innovations to close material loops and reduce waste in the food industry. Yet, the success of such strategies also depends on the quantity, quality and environmental footprint of agricultural raw materials supplied from the farm sector. There is thus a clear need to connect upstream analyses of farm-level technical efficiency and service use with the downstream sustainability agenda in food processing and the broader food industry [3,12,23–27].

Jiangsu Province possesses rich agricultural natural resources and has both geographical and economic advantages, making it a crucial commodity grain production base in China. It serves as a dominant area for single-season japonica rice within the middle and lower reaches of the Yangtze River and stands as southern China's largest production zone for japonica rice, contributing approximately 30% of the national japonica rice cultivation area. In recent years, Jiangsu's annual rice planting area has been around 2.24 million hectares, with a total output of approximately 19.6 billion kilograms [5]. At the same time, Jiangsu is located in one of the regions where mechanization services, socialized agricultural services and new-type agricultural business entities have developed rapidly, yet smallholders still constitute the main force in rice production [15]. Against this backdrop, Jiangsu provides a suitable setting to examine how APSs influence rice farmers' production decisions and technical efficiency, and to explore the implications for sustainable rice-based food systems and the rice-processing industry that relies on Jiangsu rice as a key raw material.

Drawing on field survey data from 455 rice farmers in Jiangsu Province, this paper analyzes how participation in different service links—such as land preparation, planting, plant protection and harvesting—affects rice production and technical efficiency. Specifically, we address the following research questions:

- Does participation in APSs improve rice production technical efficiency for small-scale rice farmers in Jiangsu Province?
- Do different types of productive services and service links have heterogeneous effects on rice farmers' technical efficiency, with distinct implications for sustainability (e.g., mechanization versus chemical-input services)?
- How do the effects of APSs on technical efficiency differ between traditional smallholders and new-type agricultural business entities, and what does this imply for the sustainable development of rice-based food systems?

In line with Chinese policy documents on 'new-type agricultural business entities,' we define traditional smallholders as ordinary rural households that cultivate rice on relatively small, often fragmented plots and are not registered as family farms, professional cooperatives or agricultural enterprises. New-type agricultural business entities refer to registered family farms, large-scale grain growers and professional farmer cooperatives that manage larger, more contiguous areas of land and typically employ more specialized machinery and hired labor. In our sample, we observe 237 traditional smallholder households and 218 new-type agricultural business entities, which provides sufficient observations for the heterogeneity analysis conducted in Section 5.

We also acknowledge the possibility of endogeneity between APS adoption and technical efficiency—more efficient farmers may be more likely to use services, and unobserved managerial ability may affect both. In our empirical analysis, we use a one-step stochastic frontier model with rich controls for household, farm and regional characteristics to limit omitted-variable bias, but we interpret the estimated relationships primarily as associations rather than strict causal effects, and we return to this limitation in Section 8.

By answering these questions, this study makes three contributions. First, it enriches the growing literature on APSs by providing micro-level evidence on how service participation affects rice production efficiency in one of China's major japonica rice production regions. Second, it distinguishes between different service links and business entities, thereby clarifying the heterogeneous effects of APSs on technical efficiency and helping reconcile mixed findings in the existing literature [2,4,6,9,11,14–22,28,29]. Third, by explicitly linking stage-specific APSs and technical efficiency to the sustainable development of rice-based food systems and the food industry, this study connects farm-level efficiency outcomes to the broader sustainability agenda in food processing, waste valorization and sustainable packaging [1–3,12,23–27].

2. Literature Review and Conceptual Framework

2.1. Agricultural Productive Services, Mechanization and Smallholders in China

China's rapid development of APSs is closely tied to rural labor transfer and the mechanization of grain production. APSs include mechanized land preparation, planting, plant protection, harvesting and other services provided by specialized organizations, cooperatives or large farmers. These services enable smallholders to access machinery and technology without owning the equipment themselves, thereby alleviating capital constraints and labor shortages [4,10,15,19,28].

Empirical studies show that APSs and mechanization services can increase labor productivity and allow farmers to reallocate labor to off-farm employment, while maintaining or even improving agricultural output [4,14]. At the same time, the structure of farm size is changing. Yan et al. [9] and Li et al. [6] documented how expanding farm size and the development of socialized services go hand in hand, with services making it easier to cultivate larger areas of land efficiently. However, Li and Sicular [8] and Li et al. [7] note that ageing and migration can also reduce the quality of on-farm labor, with ambiguous effects on efficiency. Against this background, APSs have become an important channel for integrating smallholders into modern, increasingly mechanized rice production systems.

2.2. Agricultural Productive Services and Technical Efficiency

A central question in the literature is whether and how APSs improve farm-level technical efficiency. Several studies find that APSs, by providing access to modern machinery, improved technologies and specialized knowledge, can reduce production costs and enhance efficiency [4,10,15,19,20]. For instance, Qing et al. [15] and Deng et al. [22] showed that mechanization and outsourcing services can significantly increase productivity for grain producers. Chen et al. [17] found that improved financial access raises technical efficiency, partly by facilitating investment in new technologies and services. These findings support the view that APSs can help farmers reorganize production, optimize input combinations and move closer to the production frontier.

However, other studies highlight possible negative or ambiguous effects. Albore [30] and Xue et al. [21] point out that service cooperatives and outsourcing arrangements can suffer from coordination problems, information asymmetries and imperfect monitoring, which may lead to inefficient performance or even lower technical efficiency. Ji et al. [18] showed that participation in agricultural technical services can, under some conditions, be associated with reduced technical efficiency, especially when service quality is low or not tailored to local conditions. Overall, the literature has not reached a consensus on how APSs affect technical efficiency, suggesting that the direction and size of impacts may depend on service type, implementation quality and farmer characteristics.

2.3. Heterogeneous Effects by Service Type and Production Stage

A growing body of work emphasizes that not all services are alike; rather, different types of services and production stages may have distinct effects on technical efficiency. On the one hand, studies such as Ji et al. [18] argue that labor-intensive services that mainly substitute for manual labor may have limited or even negative impacts on efficiency if they primarily reduce labor input without improving technology or management. Albore [30] and Xue et al. [21] also caution that when service quality is difficult to observe, low-quality providers can enter the market, leading to suboptimal outcomes.

On the other hand, several studies emphasize the positive role of technology- and capital-intensive services. Tang et al. [19] found that production services can reduce rice production costs, while Li et al. [29] showed that mechanized pesticide application can help reduce pesticide use and risk. Picazo-Tadeo and Reig-Martínez [31] and Ai et al. [28] provide evidence that outsourcing and socialized services can improve efficiency when services are delivered by capable providers and when farmers have the knowledge to supervise and integrate them into their production decisions. These mixed findings highlight the importance of distinguishing between different stages—such as land preparation, sowing, fertilization, pesticide application and harvesting—when evaluating the technical efficiency effects of APSs.

2.4. APSs, Sustainability and Rice-Based Food Systems

Beyond their effects on yields and costs, APSs have important implications for the environmental sustainability of agricultural production and for the performance of food supply chains as a whole. Recent work shows that APSs can contribute to a low-carbon agricultural transition by encouraging larger-scale operations, promoting technology upgrading and reducing carbon emission intensity in major grain-producing areas [12]. At the same time, the efficiency and environmental profile of upstream agricultural production are critical determinants of the performance of green agricultural product supply chains, which seek to minimize environmental burdens across production, processing, logistics and retail [27].

In rice-based food systems, stage-specific APSs can influence several sustainability-relevant outcomes. Mechanization services in land preparation, sowing and harvesting may reduce drudgery and improve the efficiency of energy and labor use, but they also affect fuel consumption and soil structure. Services for fertilization and pesticide application directly shape the intensity, timing and spatial distribution of chemical inputs, with implications for nutrient runoff, water quality, biodiversity and human health. When APS providers rely on standardized, input-intensive service packages—such as unified fertilizer and pesticide application plans or bundled prevention-and-control programs—they may facilitate over-application and weaken farmers' incentives to tailor input rates to local soil and crop conditions, thereby undermining environmental sustainability even when yields increase [32–34]. Conversely, when APSs are used to diffuse precision agriculture, soil testing, site-specific nutrient management and integrated pest management, they can help reduce chemical intensity and improve both technical and environmental efficiency [1,2,12,29,32].

The sustainability implications of APSs extend beyond the farm gate to the rice-based food industry. Sustainability indicators for rice and wheat supply chains emphasize that upstream resource-use efficiency, environmental performance and quality control are key determinants of supply chain resilience and sustainability [3,27]. Rice processors must manage grain quality and by-product streams (bran, husks, broken rice) that can be used for feed, energy or further processing. As recent studies on sustainable food processing and waste valorization show, agro-food by-products can be transformed into novel adsorptive

materials, novel foods and sustainable packaging materials [23–25]. The volume and composition of these by-products, as well as their embedded environmental footprint, depend partly on upstream production practices and input-use patterns, which APSs help shape. Understanding the stage-specific effects of APSs on technical efficiency is therefore important not only for farm-level performance but also for the sustainability of rice-based food systems and the food industry.

2.5. Conceptual Framework for This Study

Drawing on the literature reviewed above, this study develops a conceptual framework that links APSs, production stages, service combinations and technical efficiency in rice production. The framework highlights three main channels: (i) factor substitution and capital deepening, (ii) technology and information transmission, and (iii) stage-specific operational characteristics and service combinations. These channels underpin the mechanisms and hypotheses analyzed in the next section.

3. Mechanism and Research Hypotheses

3.1. Mechanism

The expansion of APSs is recognized as a key driver of modern agricultural development. Building on the notion of division of labor in agriculture [13], APSs allow specialized providers to supply machinery, technology and management services to smallholders, transforming the organization of production and potentially improving technical efficiency.

First, APSs can promote capital deepening and factor substitution. By providing access to machinery and advanced technologies, services enable farmers to substitute capital for labor and animal power, especially in labor-intensive stages such as land preparation, sowing and harvesting. In labor-scarce contexts, this substitution can alleviate production bottlenecks, ensure timely operations and improve technical efficiency [4,10,14,15,19,28].

Second, APSs can serve as a vehicle for technology diffusion and information transmission. Service providers often possess specialized knowledge about machinery operation, input use and crop management. Through repeated interactions, farmers can learn from providers and gradually improve their own decision-making, thereby reducing technical inefficiency [2,11,17,20,29,32]. When combined with training and extension, APSs can help disseminate improved practices such as soil testing, site-specific nutrient management and integrated pest management.

Third, the impact of APSs on technical efficiency depends on stage-specific characteristics and the quality of service provision. In stages where operations are highly standardized and easily monitored (e.g., land preparation and harvesting), specialized services can exploit economies of scale and deliver consistent quality, thereby improving efficiency [6,10,15,19,21,22,28,29]. In contrast, in stages where input use must be tailored to local conditions (e.g., fertilization and pesticide application), poor matching between standardized service packages and field conditions, as well as information asymmetries and weak monitoring, can lead to overuse of inputs and lower technical efficiency [1,2,9,18,19,21,30,32].

Finally, farmers differ in the breadth of service use. Some rely on services in only a few stages, others adopt services in multiple stages and a minority outsource nearly all operations. In principle, the breadth of service use can affect both the potential gains and the risks of outsourcing. Selective outsourcing may allow farmers to concentrate their own labor and management on stages where they have a comparative advantage while drawing on specialized providers where external expertise or machinery is most

valuable. At the same time, very broad or full-process outsourcing might either enhance coordination and access to advanced technologies or, if monitoring is weak, attenuate farmers' incentives and capacity to learn, supervise and adapt, with ambiguous net effects on technical efficiency. Figure 1 summarizes the conceptual mechanisms linking APSs, stage-specific characteristics, service combinations and technical efficiency.

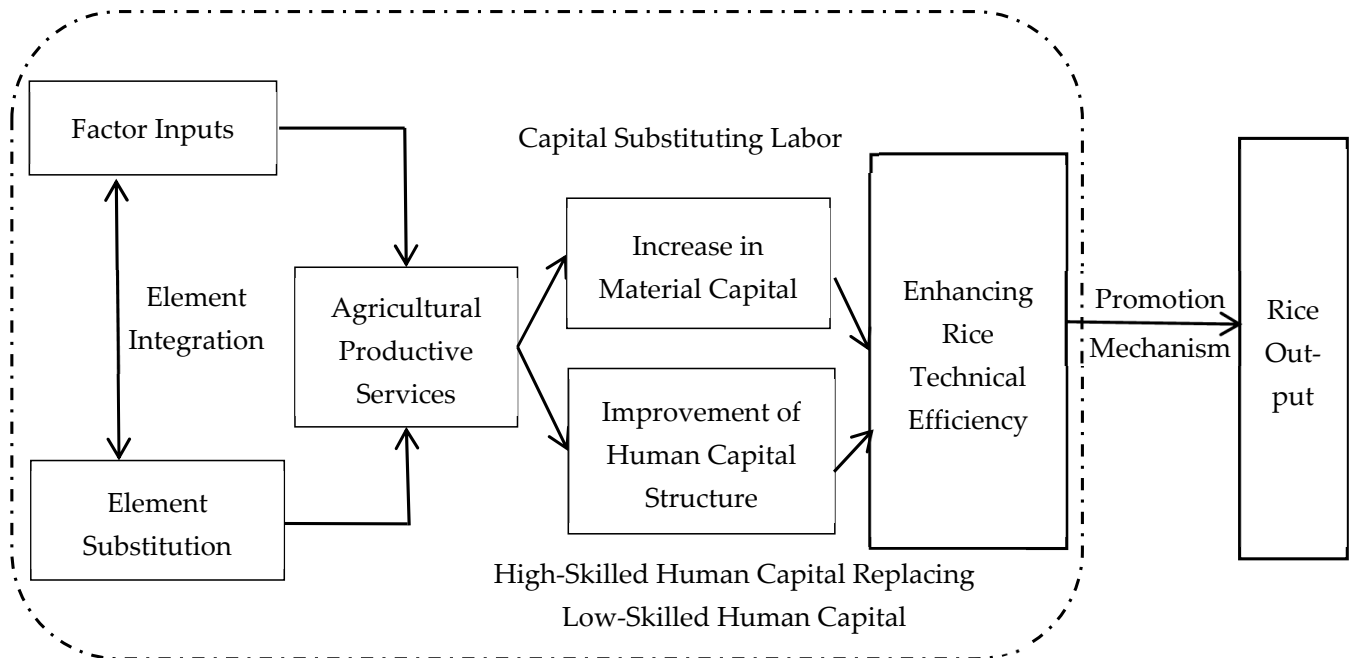


Figure 1. Mechanism diagram showing impact of agricultural productive services on technical efficiency in rice production.

3.2. Research Hypotheses

Building on the above mechanism analysis and existing empirical studies [2,4,6,9,11,14–22,28–32], we propose the following research hypotheses:

Hypothesis 1. *Agricultural productive services generally enhance the technical efficiency of rice production.*

This hypothesis corresponds to the overall effect of service use: by supplying machinery, technology and specialized labor, APSs are expected to help farmers reorganize production, improve the timeliness and quality of field operations and better coordinate input use and management, thereby reducing technical inefficiency.

Hypothesis 2. *The effects of agricultural productive services on technical efficiency are heterogeneous across production stages.*

Hypothesis 2a. *Services in land preparation, sowing and harvesting are positively associated with technical efficiency in rice production.*

Hypothesis 2b. *Services in fertilization and pesticide application may have weaker or even negative associations with technical efficiency when service quality is low or poorly matched to local conditions.*

This hypothesis reflects the idea that labor-saving, highly mechanized stages benefit from specialization and scale economies, whereas stages with complex information and

environmental externalities are more sensitive to problems of service quality, information asymmetry and supervision.

Hypothesis 3. *The relationship between the breadth of service use and technical efficiency is non-linear, with farmers using a moderate range of services achieving higher technical efficiency than those using either very few services or full-process services.*

This hypothesis connects farmers' service-use strategies with technical efficiency: a balanced combination of self-production and outsourcing may be more conducive to learning, monitoring and efficient resource allocation than either minimal service use or excessive reliance on external services.

4. Model Specification and Variable Selection

4.1. Data Collection and Questionnaire Design

This study uses cross-sectional survey data collected during 2021–2022 from 455 rice farmers in Jiangsu Province. A multi-stage sampling strategy was adopted. First, [C] counties were selected as major japonica rice-producing counties representing different subregions of Jiangsu, based on indicators of rice sown area and yield and overall regional representativeness. Second, within each sampled county, [T] townships with relatively large rice planting areas and active development of agricultural productive services were chosen in consultation with local agricultural departments. Third, within these townships, [V] administrative villages engaged in rice cultivation were selected, and within each village, a list of rice-producing households was constructed and households were randomly sampled. The survey collected detailed information on household characteristics, land endowments, rice planting area, input use, APS adoption at different stages, rice output and income composition.

Enumerators received training before fieldwork, and questionnaires were pre-tested and refined. For key variables such as rice output and land area, enumerators cross-checked reported values with village cadres or production records where possible. After excluding incomplete or clearly inconsistent responses, the final sample includes 455 rice households, providing a rich micro-level dataset for analyzing stage-specific APSs and technical efficiency.

Based on survey questions regarding registration status, organizational form and cultivated area, each rice-producing unit in the sample is classified as either a traditional smallholder or a new-type agricultural business entity. Traditional smallholders are ordinary rural households engaged in rice cultivation that are not registered as family farms, professional cooperatives or agricultural enterprises. New-type agricultural business entities include registered family farms, professional farmer cooperatives and large-scale growers that satisfy provincial criteria for 'new-type' entities (e.g., minimum managed area and business registration). In total, 237 observations are classified as traditional smallholders and 218 as new-type agricultural business entities, ensuring that both groups have sufficient sample size for the heterogeneity comparisons reported in Section 5.4.

4.2. Stochastic Frontier Production Function

To measure technical efficiency in rice production, we adopt a stochastic frontier analysis (SFA) framework. The production frontier can be specified as:

$$\ln Y_i = f(\ln X_{1i}, \dots, \ln X_{ki}; \beta) + v_i - u_i,$$

where Y_i is rice output (or yield) for household i ; $X_{1i}, \dots, X_{ki}$ are inputs such as seeds, fertilizers, pesticides, labor and machinery services; β is a vector of parameters; v_i is a

two-sided random error term capturing statistical noise, assumed to follow a normal distribution $N(0, \sigma_v^2)$; and u_i is a non-negative random variable representing technical inefficiency, typically assumed to follow a half-normal distribution [26].

In this study, Y_i is measured as the yield of rice per hectare. Main inputs include expenditure per hectare on seeds, chemical fertilizers, pesticides and machinery (including APS-related machinery services), as well as labor input. Land input is implicitly accounted for through the per-hectare specification. Following existing studies [4,6,10,15–22,29], we use a flexible functional form to capture potential non-linearities and interactions among inputs.

Technical efficiency (TE) for household i is defined as:

$$TE_i = \exp(-u_i),$$

which takes values between 0 and 1, with higher values indicating greater efficiency.

4.3. Technical Inefficiency Model and APS Variables

To analyze how APSs affect technical efficiency, we adopt the one-step approach proposed by Battese and Coelli [26], in which the inefficiency term u_i is modeled as:

$$u_i = m_i + \varepsilon_i,$$

where m_i is a function of explanatory variables and ε_i is a non-negative random term. Specifically, we specify:

$$m_i = \delta_0 + \delta_1 \text{APS_exp}_i + \delta_2 S_i + \delta_3 H_i + \delta_4 F_i,$$

where APS_exp_i is total APS expenditure per hectare; S_i is a vector of stage-specific APS variables (e.g., indicators for using services in land preparation, sowing, fertilization, pesticide application and harvesting); H_i captures household characteristics (education of household head, age, share of non-agricultural income, participation in agricultural training, etc.); and F_i includes farm and regional characteristics (rice planting area, type of business entity, village dummies, etc.). A negative coefficient on an explanatory variable in m_i implies that the variable reduces technical inefficiency and thus increases technical efficiency.

By embedding APS variables directly into the inefficiency term rather than treating efficiency as exogenous, the one-step approach avoids the potential bias associated with two-step procedures and allows us to examine the channels through which APSs influence technical efficiency [2,9,17,20,26,31].

5. Empirical Results Analysis

5.1. Estimation Results for the Rice Production Function

The one-step stochastic frontier model fits the data well, and the variance parameters indicate that a substantial share of the composite error term is attributable to technical inefficiency rather than pure noise, suggesting that the stochastic frontier framework is appropriate for analyzing rice production in Jiangsu.

In the production function, expenditures on seeds, fertilizers, pesticides and machinery are all positively related to rice output, as expected. The elasticities of output with respect to these inputs are generally reasonable and consistent with earlier studies on rice production in China and other Asian countries [1,2]. The coefficient on labor is positive but relatively small, reflecting the increasing role of machinery and services in rice production and the partial substitution of capital for labor [4,14]. Overall, the results suggest that the estimated frontier captures key input–output relationships in Jiangsu rice production.

Table 1 presents the descriptive statistics of the main variables in the production function model and shows that the average rice yield for farmers is approximately 8869.5 kg per hectare, with a minimum of 7500 kg per hectare and a maximum of 9750 kg per hectare. The average investment in seeds within agricultural inputs is 3900 Chinese yuan per hectare, while the investment in fertilizers is 3534 yuan per hectare, pesticides amount to 2625 yuan per hectare, labor costs are 3975 yuan per hectare, and machinery investment is 3525 yuan per hectare. Significant disparities between the highest and lowest values of production inputs and outputs highlight notable variations in input–output levels and structures among farmers, which may be attributed to differences in technical efficiency in rice production.

Table 1. Input situation of farmers' rice output.

Variables	Mean	Standard Deviation	Minimum	Maximum
Output (KG/Hectare)				
Rice Yield	8869.5	78.7	7500	9750
Input (Yuan/Hectare)				
Seed Input	3900	67.2	900	6000
Fertilizer Input	3534	336.1	751.5	22,243.5
Pesticide Input	2625	34.9	300	3150
Labor Input	3975	120.5	0	7950
Machinery Input	3525	123.4	0	9165

Beyond the potential influence of production service expenditure on technical efficiency in rice production, other elements—such as the household head characteristics, family economic conditions, and production management strategies—also contribute to its variation. Thus, the empirical analysis model incorporates the following control variables, which are presented in Table 2.

Table 2. Variable description.

Variables	Variable Definitions and Assignments	Mean	Standard Deviation	Minimum	Maximum
Core Explanatory Variables					
Sowing Service Expenditure	Cost of Purchased Services per Hectare for Seedling Cultivation Stage (Unit: Yuan/Hectare)	619.29	79.762	0.00	9000
Land Preparation Service Expenditure	Cost of Purchased Services per Hectare for Tillage Stage (Unit: Yuan/Hectare)	1821.72	61.914	735	6600
Fertilization Service Expenditure	Cost of Purchased Services per Hectare for Fertilization Stage (Unit: Yuan/Hectare)	761.87	79.447	0.00	4500
Pesticide Service Expenditure	Cost of Purchased Services per Hectare for Pesticide Stage (Unit: Yuan/Hectare)	382.62	36.273	0.00	1500
Harvesting Service Expenditure	Cost of Purchased Services per Hectare for Harvesting Stage (Unit: Yuan/Hectare)	932.7	14.754	300	1425
Control Variables					
Household Head Basic Characteristics					
Household Head Gender	Male = 1, Female = 2	1.352	0.478	1	2

Table 2. *Cont.*

Variables	Variable Definitions and Assignments	Mean	Standard Deviation	Minimum	Maximum
Household Head Age	Under 30 years old = 1, 31–40 years old = 2, 41–50 years old = 3, 51–60 years old = 4, Over 60 years old = 5	3.360	0.965	1	5
Household Head Education Level	No formal education = 1, Primary school and below = 2, Junior high school = 3, High school or vocational school = 4, College and above = 5	3.156	0.895	1	5
Household Economic Characteristic					
Proportion of Non-Agricultural Income in Household	0.2 and below = 1, 0.2–0.4 = 2, 0.4–0.6 = 3, 0.6–0.8 = 4, 0.8 and above = 5	3.607	0.684	1	5
Production and Management Characteristic					
Cultivated Area	Less than 1 hectare = 1, 1–2 hectares = 2, 2–4 hectares = 3, 4–10 hectares = 4, More than 10 hectares = 5	4.026	1.193	1	5
Level of Technical Attention					
Participation in Agricultural Technology Training in the Past Three Years	Yes = 1, No = 0	0.635	0.482	0	1
Access to Agricultural-Related Information	Yes = 1, No = 0	0.602	0.490	0	1

5.2. Overall Distribution of Technical Efficiency

Based on the estimated model, technical efficiency for the 455 rice households ranges between values close to 0.4 and values near 1, with an average efficiency level 0.78. This indicates substantial variation in how close farmers operate to the frontier and suggests considerable room to further improve rice production performance in Jiangsu. Some farmers are already operating near the frontier, while others lag significantly behind.

5.3. Determinants of Technical Inefficiency

The estimated technical inefficiency equation shows that APS variables play an important role in explaining differences in technical efficiency. Total APS expenditure per hectare significantly reduces technical inefficiency, implying that, on average, service use improves rice production efficiency, consistent with Hypothesis 1 and the view that APSs are a new type of input embedding machinery, technology and management into smallholder production [2,10,17,20,28,31].

Among the control variables, several patterns emerge. Education of the household head significantly reduces technical inefficiency, indicating that more educated farmers manage production and services more efficiently. The share of non-agricultural income in total household income has a positive effect on technical inefficiency, suggesting that households more reliant on off-farm work may devote less attention and high-quality labor to rice production, leading to lower efficiency. Rice planting area has a significant negative effect on technical inefficiency, implying that larger-scale operations are associated with higher technical efficiency, possibly because they can better exploit mechanization and service use [4,6,8,9]. Participation in agricultural technology training in the previous year also significantly reduces technical inefficiency, highlighting the importance of training in strengthening farmers' ability to adopt and supervise productive services. Overall, these results underscore that both service use and household characteristics shape technical efficiency.

5.4. Heterogeneity Analysis

5.4.1. Heterogeneity by Number of Service Stages

To explore how the breadth of service use is related to technical efficiency, we group farmers according to the number of production stages in which they use services (0–1, 2–3 and 4–5 stages). Conditional on the controls included in the stochastic frontier model, farmers who use services in a moderate number of stages (2–3) tend to have slightly higher mean technical efficiency (i.e., lower technical inefficiency) than those who either rely on very few services (0–1 stage) or outsource almost all operations (4–5 stages). This association is consistent with the non-linear relationship anticipated in Hypothesis 3; however, given the cross-sectional nature of the data and the potential endogeneity of service adoption, we interpret these patterns as descriptive correlations rather than strict causal effects.

A moderate breadth of service use allows farmers to take advantage of specialized machinery and technical support in key stages while still retaining active roles in other stages, which maintains their incentives to learn, monitor and adapt decisions to local conditions. By contrast, very limited service use may prevent farmers from fully benefiting from mechanization and specialization, whereas excessive reliance on full-process services may weaken farmers' incentives to monitor service quality and invest in their own skills, potentially amplifying information asymmetries and moral hazard.

5.4.2. Stage-Specific Effects of Productive Services

To investigate stage-specific effects, we include separate variables for the use of services in land preparation, sowing, fertilization, pesticide application and harvesting. The estimation results reveal a clear asymmetry. Services in land preparation, sowing and harvesting are associated with significantly lower technical inefficiency, indicating positive effects on technical efficiency. These stages are highly mechanized and relatively standardized; specialized providers can exploit economies of scale, ensure timely operations and deliver consistent quality, thereby improving efficiency [6,10,15,19,21,22,28,29].

In contrast, fertilization and pesticide application services do not consistently improve technical efficiency, and in some specifications they are associated with higher inefficiency. These results suggest that current service provision in fertilization and pesticide application may face problems such as insufficient tailoring of input packages to local soil and pest conditions, uneven service quality and inadequate technical guidance on environmentally friendly practices [1,2,9,18,19,21,29,32]. Under such conditions, service providers may encourage overuse of chemical inputs, increasing costs and environmental pressure while failing to improve yields, which undermines both technical and environmental efficiency.

5.5. Robustness Check

To assess the robustness of the main findings, we conduct several checks. First, we estimate alternative specifications of the production function Cobb–Douglas vs. translog and find that the qualitative effects of APS expenditure and stage-specific services on technical inefficiency remain consistent. Second, we use alternative measures of service intensity (e.g., binary indicators vs. expenditure shares) and confirm the pattern of positive effects for land preparation, sowing and harvesting services and weaker or negative effects for fertilization and pesticide services. Third, we re-estimate the model excluding possible outliers in output or input use; the main conclusions are unchanged. These robustness checks support the reliability and interpretability of the empirical results.

6. Discussion and Implications

6.1. Discussion of Main Findings

This paper set out to examine how APSs influence the technical efficiency of rice farmers in Jiangsu Province, how different service types at distinct production stages affect technical efficiency and how different combinations of service stages are associated with efficiency outcomes. Our analysis is conducted at the farm level and focuses on APS adoption and technical efficiency; we do not directly model rice quality, the stability of supply, greenhouse gas emissions or downstream processing performance. Nevertheless, the results have indirect implications for the sustainability of rice-based food systems and the rice-processing industry, insofar as changes in farm-level efficiency and input-use patterns can affect the quantity, reliability and environmental footprint of rice supplied as a raw material. These links are discussed conceptually in the paper and point to promising directions for future research that would explicitly integrate farm-level APSs and technical efficiency with downstream indicators of food-system and food-industry performance.

First, TE at the production frontier does not automatically imply lower input intensity or a smaller environmental footprint. First, the one-step stochastic frontier results show that total expenditure on APSs per hectare is associated with significantly lower technical inefficiency, indicating that, on average, service use is linked to higher technical efficiency. This supports the view that productive services are a new type of input that embeds machinery, technology and management into smallholder production [2,10,17,20,28,31]. For Jiangsu rice farmers, APSs appear to compensate for constraints in capital, labor and technology, enabling them to reorganize production and move closer to the frontier. From a sustainability perspective, higher technical efficiency can, in principle, reduce resource use and environmental pressure per unit of rice produced; however, aggregate environmental outcomes ultimately depend on how total output, input intensity and technology choices adjust in response to service adoption. Our results therefore speak primarily to potential per-unit efficiency gains rather than to realized changes in absolute environmental footprints [1,2].

Second, the stage-specific analysis reveals clear heterogeneity in the effects of different services. Services in land preparation, sowing and harvesting have positive effects on technical efficiency, while services for fertilization and pesticide application tend to reduce efficiency or have no significant effect. This pattern is consistent with the idea that highly mechanized and standardized operations benefit from specialization and scale economies, whereas technology- and information-intensive links such as fertilization and pesticide application are more vulnerable to misallocation of inputs and quality problems when monitoring is imperfect [4,6,9,18,19,21,22,29]. Land-preparation, sowing and harvesting services mainly substitute for manual labor, exploit economies of scale and ensure timely operations, thereby improving efficiency [6,10,15,19,21,22,28,29]. In contrast, fertilization and pesticide services may rely on standard packages that are not fully adapted to local conditions, leading to over-application of inputs, increased costs and lower technical efficiency even when they save time and labor [1,2,9,18,19,21,29,32].

Third, the heterogeneity analysis by number of stages covered by services suggests that farmers who use services at a moderate number of stages tend to exhibit slightly higher technical efficiency than those who either rely on very few services or outsource almost all stages. These differences are modest and should be interpreted as descriptive correlations rather than as strong causal effects. One possible explanation is that a balanced combination of self-production and outsourcing allows farmers to take advantage of specialized machinery and technical support in key stages while still retaining active roles in decision-making and supervision. Conversely, very limited or very extensive outsourcing may provide

fewer opportunities to exploit complementarities between farmers' own skills and external services. However, because our data do not include direct indicators of farmers' learning, monitoring or disciplinary efforts, this interpretation should be viewed as a plausible mechanism rather than as an empirically verified channel.

Beyond APSs, the results show that technical efficiency is also associated with farmer characteristics, economic structure, production scale and technology acquisition. Higher education levels of household heads are positively related to technical efficiency, highlighting the importance of human capital for absorbing and supervising services. A larger share of non-agricultural income is associated with lower technical efficiency, suggesting that households more engaged in non-farm work may devote less attention and high-quality labor to rice production. Larger planting areas and participation in agricultural training both enhance technical efficiency, indicating that scale and technology dissemination remain key levers for improving production performance in Jiangsu's rice sector [4,6–11,15,16,29].

6.2. Theoretical Contribution

From a theoretical perspective, this study contributes to the literature in several ways. First, by embedding service variables directly into the inefficiency term of a one-step stochastic frontier model, the analysis provides evidence on the channels through which services influence technical efficiency rather than treating efficiency as exogenous [2,9,17,20,26,31]. Second, by distinguishing stage-specific services, it clarifies why previous empirical studies have reported mixed results on the impact of services on efficiency and productivity [2,4,6,9,14–22,28,29,32]. The findings show that labor-saving, standardized stages (land preparation, sowing, harvesting) and technology-intensive, information-intensive stages (fertilization, pesticide application) influence efficiency in very different ways. Third, by linking APSs to sustainability and rice-based food systems, the paper integrates the literature on socialized agricultural services with emerging research on green supply chains and sustainable food processing [1–3,12,20,23–27,32].

6.3. Policy and Managerial Implications

These results have indirect implications for sustainable rice-based food systems and the food industry. Changes in farm-level technical efficiency are conceptually linked—through the quantity of output per unit of input and patterns of input use—to the potential quality, reliability and environmental footprint of rice supplied to processors. Sustainability indicators for rice and wheat supply chains emphasize that upstream resource-use efficiency and quality control are key determinants of overall supply chain sustainability and resilience [3,27]. Our findings suggest that APSs—if properly designed and regulated—are associated with more efficiently organized production in stages such as land preparation, sowing and harvesting, which may, in principle, support a lower-carbon and more reliable flow of raw material to mills and food manufacturers [1,12]. Conversely, APSs that reinforce input-intensive fertilization and pest-control practices may be associated with higher chemical intensity and a greater environmental burden carried forward into the processing stage, potentially undermining green supply-chain initiatives [1,2,27,29,32]. It is important to note that our data do not contain direct measures of rice quality, supply stability or carbon emissions; these downstream implications are discussed as plausible pathways based on the existing literature rather than as outcomes observed in our sample.

This upstream perspective complements recent work on sustainable food processing, waste valorization and packaging innovations, which shows how agro-food wastes and by-products can be transformed into adsorptive materials, novel foods and sustainable antimicrobial packaging films [23–25]. Those studies focus on downstream technologies and circular-economy strategies; our analysis highlights that upstream service design is

equally critical because it shapes production volumes, input-use patterns and the environmental profile of raw materials that enter the rice-processing industry. Taken together, these strands of research suggest that policies to promote sustainability in rice-based food systems must address both downstream innovations and upstream service structures.

In terms of policy and managerial implications, the findings suggest that expanding APSs is necessary but not sufficient. Policy makers should: (i) continue to support the development of specialized service providers, cooperatives and service-oriented enterprises, particularly in mechanized stages where services clearly improve efficiency; (ii) introduce performance-based criteria and environmental standards for fertilization and pesticide services, encouraging providers to adopt precision fertilization, integrated pest management and environmentally friendly practices [1,2,12,29,32]; and (iii) promote modular and flexible service packages that allow farmers to choose combinations of stages according to their own endowments, risk preferences and learning objectives. Rice processors and retailers pursuing sustainable sourcing strategies can also integrate APS-related criteria into procurement contracts and certification schemes, co-investing in service models that support both technical and environmental efficiency along the rice-based food chain [3,12,23–27].

7. Limitations and Future Research

This study also has several limitations that suggest directions for future research. First, the analysis is based on cross-sectional data from a single year and one province. While Jiangsu is a major rice-producing region with advanced APS markets, the results may not fully capture dynamic adjustments or regional heterogeneity in service development and technical efficiency. Future work could use panel data from multiple regions to examine the evolution of APSs and efficiency over time and to explore spatial heterogeneity more systematically.

Second, the present study mainly measures service use through expenditure and stage-specific indicators, without fully capturing qualitative aspects such as service timeliness, reliability and environmental performance. Future research could combine quantitative surveys with qualitative case studies and field experiments to better understand contractual arrangements, monitoring mechanisms and the behavioral responses of both farmers and service providers.

Third, there may be endogeneity between service use and technical efficiency, as more efficient farmers may be more likely to adopt services and unobserved factors (for example, managerial ability or risk preferences) may jointly affect both. The one-step stochastic frontier framework avoids the bias associated with two-step efficiency models by estimating the production and inefficiency equations jointly, but it does not, by itself, eliminate potential endogeneity between APSs and technical efficiency due to omitted variables or selection. Our estimates should therefore be interpreted as conditional associations rather than definitive causal effects. Future work could use instrumental-variable strategies, panel data or experimental and quasi-experimental designs to more rigorously identify the causal impact of APSs on technical efficiency and related environmental outcomes.

Fourth, this paper focuses on technical efficiency and does not explicitly measure environmental efficiency, such as greenhouse gas emissions or nutrient losses. Given the growing emphasis on low-carbon and green agricultural development [1,2,12,20,27,32], future research could integrate environmental outputs or undesirable outputs into a joint technical-environmental efficiency framework to analyze trade-offs between yield, efficiency and environmental outcomes.

8. Conclusions

This paper uses micro-survey data from 455 rice farmers in Jiangsu Province and a one-step stochastic frontier production function to investigate how APSs influence technical efficiency in rice production and to explore the implications for sustainable rice-based food systems and the rice-based food industry.

The analysis leads to three main conclusions. First, APSs as a whole improve the technical efficiency of rice production: higher service expenditure per hectare is associated with lower technical inefficiency, indicating that services play a positive role in helping smallholders approach the production frontier [2,4,9,10,14–17,19,20,22,28]. Second, the effects of services are heterogeneous across production stages. Services for land preparation, sowing and harvesting significantly increase technical efficiency, reflecting the advantages of mechanization and standardization in these stages, whereas services for fertilization and pesticide application tend to reduce technical efficiency or have no significant effect, suggesting that current service provision in these links may face problems such as insufficient tailoring to local conditions, uneven quality and inadequate technical guidance [1,2,4,6,9,18,19,21,22,29,32]. This asymmetry is crucial for understanding the sustainability implications of APSs, since it is precisely in fertilization and plant protection that environmental risks from nutrient losses and pesticide pollution are highest [1,2,12,27,29,32].

Third, the relationship between the breadth of service use and technical efficiency is non-linear. Farmers using a moderate range of services (multi-stage services) generally have higher technical efficiency than those using services in only a few stages or purchasing full-process services. This implies that combining self-production with selective outsourcing can better exploit the complementarity between farmers' own knowledge and specialized services than either very limited or complete outsourcing.

Overall, the results underscore that APSs are a powerful lever for transforming rice production systems in ways that affect both farm-level performance and the sustainability of rice-based food systems and the food industry. For Jiangsu and similar major rice-producing regions, policy makers should attach equal importance to optimizing the structure and quality of services, strengthening technical content in fertilization and plant protection and guiding farmers toward balanced service combinations that fit their resource endowments and livelihood strategies. Rice processors and other downstream actors can also support these goals by integrating APS-related sustainability criteria into their sourcing and certification schemes [3,12,23–27]. Doing so will be essential for consolidating China's rice production capacity, safeguarding grain security and promoting the sustainable development of smallholder agriculture under the rural revitalization strategy.

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