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Research on agricultural science and technology advancement enabling the development of rural industrial incorporation from the perspective of decomposition

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Abstract: Taking China as an example in this study, we aim to reveal the enabling effects of agricultural science and technology advancement on the progress of rural industrial incorporation at a relatively more refined level. The main innovation in this study lies in the decomposition of agricultural science and technology advancement, followed by an analysis of its effect on rural industrial incorporation along both linear and non-linear dimensions. The study results show that, along the linear dimension, agricultural science and technology advancement, agricultural knowledge advancement and agricultural technology advancement play significant driving roles in the progress of rural industrial incorporation. However, although the estimated coefficient of the integration of agricultural knowledge advancement and technology advancement is positive, it is not statistically significant. Along the non-linear dimension, agricultural science and technology advancement, agricultural knowledge advancement and agricultural technology advancement all exhibit significantly positive effects across different intervals. However, although the integration of agricultural knowledge advancement and technology advancement also shows a positive effect, its significance appears only in the second interval, indicating that the effect of this variable in promoting rural industrial incorporation can be realised only under certain conditions.

Keywords: agriculture; linear; non-linear; science; industry

The advancement of rural industries forms the material foundation for agricultural and rural modernisation, with industrial incorporation being crucial to this progress. Rural industrial incorporation is the key content of promoting rural revitalisation in China. Through the vertical extension of industrial chains and the horizontal expansion of agricultural multifunctionality, the rural industrial structure has been driven toward rationalisation and advancement. This process has facilitated the evolution of fresh business forms, frameworks and attributes, thereby increasing farmers' incomes.

Although some progress has been made, rural industrial incorporation in China remains at a nascent stage, leaving substantial space for future growth. Numerous factors influence industrial development, among which scientific and technological progress serves as a key driving force, providing continuous internal momentum for industrial growth. Fully harnessing

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the abundant potential of agricultural scientific and technological advancement and boosting its driving capacity are crucial for the future convergent development of rural industries. As a fundamental motivating factor, the advancement of agricultural science and technology supports the refined progress of rural industrial incorporation, harnessing this influence to drive changes in momentum, structures and models. Although the theoretical feasibility of agricultural scientific and technological advancement strengthening the incorporation of rural industry exists, empirical verification is required to confirm whether practical outcomes align with theoretical expectations. In this study, we aim to address this issue. At the same time, given that both agricultural scientific and technological advancement and the progress of rural industrial incorporation are complex systems, the supply and reception of empowerment occur within a multidimensional framework, making the empowerment process itself a complex system. Therefore, research on this issue should focus not only on macro-level analysis but also on meso- and micro-level analyses.

Scientific and technological advancement is essentially a comprehensive description of the phenomenon of technological innovation initiated by scientific discoveries, demonstrating the strong relationship and synergy between the development of knowledge and technological progress (Hong 2015). The knowledge innovation system and the technological innovation system form the core components of the agricultural scientific and technological advancement system (Gu et al. 2007). On this basis, the research breaks down agricultural science and technology advancement and explores its effect on the progress of rural industrial incorporation. The goal is to reveal the empowerment mechanisms at a more refined level and enrich research findings in this field.

This study has certain theoretical significance. First, it helps deepen the theoretical explanation of rural industrial incorporation through the lens of agricultural science and technology advancement. Second, it promotes interdisciplinary integration of advancement-driven theory and industrial incorporation theory. In addition, this study holds practical significance. First, it provides new evidence that greatly accelerates the progress of agricultural modernisation, marking a significant step forward in the shift from conventional to contemporary farming practices. Second, it offers new insights for promoting rural industrial incorporation and enhancing rural industrial competitiveness. Third, it facilitates the smooth flow and coordinated development of resources between urban and rural areas, thereby strengthening overall economic integration and balanced progress. Fourth, it contributes to expanding farmers' income channels and improving their living standards.

Literature review

With regard to technological innovation, concerning its relationship with industrial development, Antonelli (2003) found that a significant interactive relationship exists, with scientific innovation and industrial structure evolution mutually influencing and promoting one another. Tao and Peng (2017) found that scientific innovation actively drives the upgrading of industrial structures. Zou (2024) argued that scientific and technological advancement promotes gradual industrial upgrading through methods such as the introduction of new technologies, architectural innovation, standardisation, integrated innovation and paradigm shifts. In the research results on China, Cao et al. (2024) demonstrated that agricultural science and technology advancement is pivotal in driving the deep integration of agriculture with industry and services, thereby facilitating the development of an advanced agricultural industry system. Zhu and Yan (2024) pointed out that the conversion rate of China's agricultural innovations is approximately 40%, a relatively low level that significantly constrains the role of agricultural science and technology achievements in supporting progress in rural industrial incorporation. Yao et al. (2024) demonstrated that from 2006 to 2020, the alignment between China's agricultural innovations and the progress of rural industrial incorporation exhibited a rising trend. Liu and Huang (2025) argued that there is poor connectivity between the agricultural science and technology advancement chain and the rural industrial chain, making it difficult for the innovation chain to feed back into the industrial chain. Results from the empirical study by Li and Wu (2022) revealed that the progress of rural industrial incorporation faces several challenges, including insufficient investment in scientific innovation, poor environmental conditions and lagging strategic planning. Yao (2023) found that scientific innovation not only significantly promotes the progress of rural industrial incorporation but also enhances its spatial spillover effects. Jiao and Liu (2022) discovered that the level of regional digital inclusive finance constrains the marginal effect of agricultural science and technology advancement on the progress of rural industrial incorporation. Using a coupling evaluation model, Song (2013) found that a coupling deviation phenomenon exists between rural industrial progress and scientific advancement in China.

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On a more detailed level, numerous scholars have explored the role of technological innovation as a catalyst for industrial incorporation. For example, Hou and Sun (2024) demonstrated that technological innovation propels the progress of rural industrial incorporation. Qu and You (2024) found that technological innovation, particularly information technology, provides new momentum for industrial integration. Yang (2023) discovered that technological innovation plays a mediating role in the effect of digital trade on the integrated development of modern distribution and advanced manufacturing sectors. Zhao (2019) argued that technological innovation drives industries toward advanced development through the indirect pathway of sector incorporation. Hu (2024) argued that the multidimensional influences of economic performance, technological advancements and the regulatory framework have created multiple structural adjustment paths that drive industrial integration. Fai and Von (2001) established a positive correlation between the overlap of patent technologies across industries and the degree of incorporation. Hauschildt et al. (2005) believed that technological innovation increased the necessity and possibility of industrial integration. Karvonen and Kassi (2012) found that the integration and convergence of new technologies will lead to the emergence of new industries. Hacklin (2008), Kim et al. (2015) and Heo and Lee (2019) all believed that the driving force of industrial integration came from technological innovation.

However, the research on knowledge innovation and industrial development is relatively sparse. Ngai and Pissarides (2007) emphasised the effect of knowledge innovation on the evolution of industrial sectors. Martin and Castro (2015) examined the function of knowledge innovation in industries characterised by knowledge intensity and advanced technology, and their research provided insights into the mechanisms driving innovation in these specialised markets. Ashouri et al. (2021) based their research on patient-level indicators and believed that newly proposed combined knowledge can trigger the process of industrial integration. Yan and He (2013) analysed the knowledge development activities of industrial incorporation in terms of innovation in knowledge.

The potential innovation of this study lies in the following aspects: First, it decomposes agricultural science and technology advancement, enabling a more detailed analysis of the effect of these variables on rural industrial incorporation at a more micro level. Specifically, the influence of the integration of agricultural knowledge advancement and technology advancement is a topic that has not been addressed in previous research. Second, we used linear analysis but also observed the empowering effect from a non-linear perspective.

Research hypotheses

Mechanism of agricultural science and technology innovation on rural industrial integration development. Advancement in agricultural research and technology serves as an internal driving force for the progress of rural industrial incorporation. In one respect, considering vertical extension of the industrial chain, progress in agricultural science and technology has facilitated the synergistic effects and collaborative efficiency between the upstream and downstream components of the industrial chain by enabling each link of the industrial chain, guiding the intensive allocation of various resources in the industrial chain and providing basic conditions for the integration of the industrial chain. Advanced agricultural technological innovations have more effectively promoted the interaction between the upstream and downstream sectors of the industrial chain, fostering the development of an industrial ecosystem community and driving the agricultural and rural industrial chain toward higher-end advancement.

In another respect, looking at the horizontal expansion of industrial scope, agricultural science and technology advancement has further accelerated the actualisation of the multifunctional attributes of agricultural sectors. This advancement has stimulated industrial potential, unleashed vitality and not only broadened the scope of agricultural sectors but also created opportunities for the connections among agricultural industries and sectors such as ecology, leisure and culture, thereby expanding the scope of rural industries horizontally.

> H_1: Agricultural science and technology advancement facilitates the progress of rural industrial incorporation.

The mechanism of agricultural knowledge innovation on the development of rural industry integration. In the age of the new economy, knowledge-driven innovation serves as a scientific basis for industrial progress (Luo 2024). Knowledge advancement is a form of innovation led by universities and research institutions and is characterised by breakthroughs in scientific thinking (Hong 2013). Agricultural knowledge advancement is the specific performance of knowledge innovation in the specific field of agriculture. The process of industrial integration inherently includes two links: knowledge creation and knowledge spillover (Yan and He 2013). The progress of agricultural knowledge offers comprehensive and structured support for agrarian sector growth with-

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in the framework of scientific guidance. The pioneering achievements of agricultural knowledge enrich the knowledge base of the rural industrial network and contribute to knowledge integration by strengthening foundational aspects, public welfare and dissemination. This supporting role ultimately manifests through advancements in agricultural technology, enhancement of human capital availability, commercialisation of knowledge and refinement of the management framework.

> H_2: Agricultural knowledge advancement facilitates the progress of rural industrial incorporation.

Mechanism of agricultural technology innovation on rural industrial integration development. Technological evolution and its diffusion play a crucial role in promoting industrial convergence. Enterprises are the main body of technological innovation, transforming high-tech ideas into real products and real productivity (Hong 2009). In contrast to academic institutions and research organisations focussed on progress in knowledge, agricultural technology firms are profit driven, with advancements in agricultural techniques serving as a key strategy to maximising their earnings (Chen et al. 2016).

Agricultural technology advancement has brought more significant direct effects for progress in the incorporation of rural economic sectors. Advances in technology help overcome the obstacles among various sectors within the industry, as well as between agriculture and other economic sectors (Zhao et al. 2017). These advances foster the efficient distribution of resources, investment and other essential factors across different areas. Agricultural technology advancement integrates agricultural activities with product processing, distribution and various service industries, creating stronger links among the agricultural, manufacturing and service sectors in rural areas. This process supports the broadening of the agricultural value chain; the extension of industrial activities; and, ultimately, an increase in farmers' earnings (Ma 2015). Agricultural technology advancement affects rural industrial incorporation primarily through the industrial technological structure. The spread of technological innovation across various industries leads to the merging of technologies, creating a shared technological base. This process allows industries to connect and interact with one another, facilitating the softening of borders across sectors and encouraging their gradual convergence, resulting in the development of new industry characteristics or structures (Chen 2007).

> H_3: Agricultural technology advancement facilitates the progress of rural industrial incorporation.

The functional mechanism of the integration of agricultural knowledge advancement and technology advancement in the progress of rural industrial incorporation. Advancements in knowledge play a foundational role in scientific and technological progress, serving as the basis for technological advancements (Hong 2013). They offer the conceptual framework that drives technological developments, and technological advancements enable the practical application and spread of knowledge (Ren and He 2022). The integration of agricultural knowledge advancement and technology advancement is reflected in the conversion of scientific findings into practical applications, facilitating the swift and efficient translation of discoveries into practical solutions, which fosters the rapid growth of innovative technologies, industries and emerging business models (Hong 2016).

The interaction and feedback among various entities involved in agricultural knowledge and technology development, facilitated by a collaborative system, can drive the application of these innovations within specific industries. This process enhances the productivity, profitability and competitiveness of the industry by altering factors such as industrial concentration, organisational structure, scientific needs and resource allocation. As a result, this process accelerates the advancement of rural industrial incorporation along both vertical and horizontal dimensions of the industrial structure.

> H_4: The integration of agricultural knowledge advancement and technology advancement facilitates the progress of rural industrial incorporation.

MATERIAL AND METHODS

Variable selection

The dependent variable in this study is the level of rural industrial incorporation, represented by the rural industrial incorporation index as a proxy variable. This index is calculated using the entropy method based on the dependent variable indicator system in Table 1.

Among the core independent variables in this study, agricultural science and technology advancement, agricultural knowledge advancement and agricultural technology advancement are represented by their respective indexes, which are calculated using the entropy method based on the core independent variable indicator system in Table 2. The integration of agricultural knowledge advancement and technology advancement is represented by the coupling coordination degree of agricultural knowledge advancement and agricultur-

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Table 1. Equation variables

Category		Variable designation	Variable definition
Outcome variable		rural industrial incorporation (*ric*)	rural industrial incorporation index
Independent variable	core independent variable	agricultural science and technology advancement (*asta*)	agricultural science and technology advancement index
		agricultural knowledge advancement (*aka*)	agricultural knowledge advancement index
		agricultural technology advancement (*ata*)	agricultural technology advancement index
		integration of agricultural knowledge advancement and technology advancement (*iakt*)	coupling coordination degree of agricultural knowledge advancement and agricultural technology advancement
	control variable	urbanisation level (*urb*)	proportion of urban population
		disparities in income between urban and rural (*ig*)	income ratio between urban and rural residents
		rural transportation infrastructure (*rtf*)	sum of mileage of class II, class III and class IV highways
		economic openness (*reo*)	total imports and exports / gross regional product
		agricultural mechanisation level (*aml*)	total power of agricultural machinery
		fiscal support (*fae*)	per capita agricultural fiscal expenditure
		level of human capital in rural areas (*rhc*)	average years of schooling across different educational levels

Source: Authors' own composition

al technology advancement, which is computed using the coupling coordination degree model.

In this study, we incorporated several relevant factors related to the progress of rural industrial incorporation as control variables as follows:

i) The level of urbanisation affects the allocation level of urban and rural industrial resources, which, in turn, affects the level of rural industrial incorporation. In this study, we used the proportion of urban population as the proxy variable of this index.

ii) Disparities in income between urban and rural areas influence the progress of rural industrial incorporation through channels such as consumption demand and human capital investment. In this study, we adopted the income ratio between urban and rural residents as a proxy variable.

iii) As a key indicator of rural infrastructure development, transportation networks facilitate the incorporation of rural industries by enabling the flow of information, labour and capital. In addition, they play a crucial role in enhancing the distribution of farm products, influencing the scale and spatial organisation of rural industries. In China, secondary roads primarily connect suburban areas and indirectly affect rural economies, and tertiary and quaternary roads serve as vital links between urban and rural regions, exerting a more direct economic effect (Zhou et al. 2022). To represent this factor, we used the total mileage of lower-tier and higher-tier roads as a proxy variable in this study.

iv) Economic openness facilitates the efficient distribution of assets both domestically and internationally, thereby shaping the industrial growth path within a region. In this study, we adopted the ratio of total foreign trade volume to regional gross domestic product as a proxy variable for this index.

v) The degree of mechanisation is linked to increased production efficiency, thereby driving the advancement of rural industrial incorporation. In this study, we used the overall capacity of cultivation machinery to represent this index.

vi) Fiscal support for farming reflects the extent of government support during the process of agricultural progress, directly influencing the progress of rural industrial incorporation. In this study, we adopted the *per capita* agricultural fiscal expenditure to represent this index.

vii) The education level in less developed areas is a crucial factor and a source of competitiveness for industrial development, influencing the progress,

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Table 2. Index system of dependent variable and core independent variable

Objective layer	Criterion layer	Assessment layer	Index meaning
Rural industrial incorporation index	integration of rural services	development level of primary industry-related services	proportion of economic output from primary industry-related services to the total primary industry output
	rural industrial chain extension	agricultural industrialisation management level	revenue from the core operations of the food sector as a proportion of the overall primary industry output
	fostering new agricultural business models	scale of infrastructure-based agriculture	area dedicated to infrastructure-based farming to the area of arable land
	agricultural multi function expansion	workforce participation rate in the manufacturing and service sectors	workforce participation in manufacturing and service sectors to the total employment
		development level of leisure agriculture	leisure agricultural business income to the total primary industry output
Agricultural science and technology advancement index	input	personnel input	full-time equivalent of agricultural R&D personnel
		funding investments	internal spending on agricultural research and experimental development funds
	output	paper output	major foreign search tools include Chinese agricultural science and technology papers
		patent output	volume of validated agricultural invention and utility model patent proposals
Agricultural knowledge advancement index	input	workforce contribution	full-time equivalent of research and development staff in agricultural fundamental and applied research
		funding investments	internal spending on agricultural fundamental and functional research funds
	output	paper output	count of Chinese agricultural research papers indexed by leading international search engines
Agricultural technology advancement index	input	personnel input	full-time equivalent of research and development staff in agricultural experimental work
		funding investments	internal expenditure of agricultural experimental development funds
	output	patent output	number of authorised agricultural invention and utility model patent applications

R&D – research and development
Source: Authors' own composition

upgrading and high-quality growth of the farming sector. In this study, we measured it by calculating the average years of schooling across different educational levels.

Model construction

Because of the high correlations among the core independent variables, we adopted the way of entering the equation one by one for regression analysis.

Benchmark equation. In this study, we used the ordinary least squares method to estimate the benchmark equation. The situation of the benchmark equation is as follows:

$$\ln ric_{it} = \alpha_i + \beta_1 \ln asta_{it} + \beta_2 t \ln urb_{it} + \\ + \beta_3 \ln ig_{it} + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \\ + \beta_6 \ln aml_{it} + \beta_7 \ln fae_{it} + \beta_8 \ln rhc + \mu_{it} \quad (1)$$

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$$\ln ric_{it} = \alpha_{it} + \beta_1 \ln aka_{it} + \beta_2 t \ln urb_{it} + \beta_3 \ln ig_{it} + \\ + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \beta_6 \ln aml_{it} + \\ + \beta_{7it} \ln fae_{it} + \beta_8 \ln rhc + \mu_{it} \quad (2)$$

$$\ln ric_{it} = \alpha_{it} + \beta_1 \ln ata_{it} + \beta_2 t \ln urb_{it} + \\ + \beta_3 \ln ig_{it} + \beta_4 \ln rtf_{it} + \beta_5 \ln reo + \\ + \beta_6 \ln aml_{it} + \beta_7 \ln fae_{it} + \beta_8 \ln rhc + \mu_{it} \quad (3)$$

$$\ln ric_{it} = \alpha_{it} + \beta_1 \ln iakt_{it} + \beta_2 t \ln urb_{it} + \\ + \beta_3 \ln ig_{it} + \beta_4 \ln rtf_{it} + \beta_5 \ln reo + \\ + \beta_6 \ln aml_{it} + \beta_7 \ln fae_{it} + \beta_8 \ln rhc + \mu_{it} \quad (4)$$

where: i – cross-sectional units; t – time; α_{it} – unchanging component; β_i – regression parameter for the explanatory variable; μ_{it} – denotes the residual component.

Endogeneity test. Considering that endogeneity may lead to biased estimation results in the baseline equation, we used the IV-2SLS method to test this issue.

The equation of the first stage is as follows:

$$\ln asta_{it} = \beta_1 \ln z_{it} + \beta_2 \ln urb_{it} + \beta_3 \ln ig_{it} + \\ + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \beta_6 \ln aml_{it} + \\ + \beta_7 \ln fae_{it} + \beta_8 \ln rhc_{it} + \upsilon_{it} \quad (5)$$

$$\ln aka_{it} = \beta_{0it} + \beta_1 \ln z_{it} + \beta_2 \ln urb_{it} + \\ + \beta_3 \ln ig_{it} + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \\ + \beta_6 \ln aml_{it} + \beta_7 \ln fae_{it} + \beta_8 \ln rhc_{it} + \upsilon_{it} \quad (6)$$

$$\ln ata_{it} = \beta_0 + \beta_1 \ln z_{it} + \beta_2 \ln urb_{it} + \beta_3 \ln ig_{it} + \\ + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \beta_6 \ln aml_{it} + \\ + \beta_7 \ln fae_{it} + \beta_8 \ln rhc_{it} + \upsilon_{it} \quad (7)$$

$$\ln iakt_{it} = \beta_0 + \beta_1 \ln z_{it} + \beta_2 \ln urb_{it} + \beta_3 \ln ig_{it} + \\ + \beta_4 \ln rtf_{it} + \beta_5 \ln reo_{it} + \beta_6 \ln aml_{it} + \\ + \beta_7 \ln fae_{it} + \beta_8 \ln rhc_{it} + \upsilon_{it} \quad (8)$$

where: z_{it} – instrumental element; υ_{it} – stochastic disturbance.

The equation of the second stage is as follows:

$$\ln ric_{it} = \gamma_0 + \gamma_1 \ln asta^*_{it} + \gamma_2 \ln urb_{it} + \gamma_3 \ln ig_{it} \\ + \gamma 4 \ln rtf_{it} + \gamma_5 \ln reo_{it} + \gamma_6 \ln aml_{it} + \\ + \gamma_7 \ln fae_{it} + \gamma_8 \ln rhc_{it} + \mu_{it} \quad (9)$$

$$\ln ric_{it} = \gamma_0 + \gamma_1 \ln aka^*_{it} + \gamma_2 \ln urb_{it} + \gamma_3 \ln ig_{it} + \\ + \gamma 4 \ln rtf_{it} + \gamma_5 \ln reo_{it} + \gamma_6 \ln aml_{it} \\ + \gamma_7 \ln fae_{it} + \gamma_8 \ln rhc_{it} + \mu_{it} \quad (10)$$

$$\ln ric_{it} = \gamma_{0it} + \gamma_1 \ln ata^*_{it} + \gamma_2 \ln urb_{it} + \gamma_3 \ln ig_{it} \\ + \gamma 4 \ln rtf_{it} + \gamma_5 \ln reo_{it} + \gamma_6 \ln aml_{it} \\ + \gamma_7 \ln fae_{it} + \gamma_8 \ln rhc_{it} + \mu_{it} \quad (11)$$

$$\ln ric_{it} = \gamma_{0it} + \gamma_1 \ln iakt^*_{it} + \gamma_2 \ln urb_{it} + \gamma_3 \ln ig_{it} + \\ + \gamma 4 \ln rtf_{it} + \gamma_5 \ln reo_{it} + \gamma_6 \ln aml_{it} + \\ + \gamma_7 \ln fae_{it} + \gamma_8 \ln rhc_{it} + \mu_{it} \quad (12)$$

where: γ – estimated coefficient; μ_{it} – refers to the random disturbance term.

Non-linear analysis. Referring to Hansen (1999), we constructed a panel threshold model to conduct a non-linear analysis. The following single-threshold models were established using the core independent variables as threshold variables:

$$\ln ric_{it} = \alpha_{it} + \beta_1 \ln x_{it}(x_i \le \theta_1) + \beta_2 \ln x_{it}(x_i > \theta_1) + \\ + \beta_3 \ln urb_{it} + \beta_4 \ln ig_{it} + \beta_5 \ln rtf_{it} + \\ + \beta_6 \ln reo_{it} + \beta_7 \ln aml_{it} + \beta_8 \ln fae_{it} + \\ + \beta_9 \ln rhc_{it} + \mu_{it} \quad (13)$$

where: x_{it} – index of agricultural science and technology advancement and its decomposition; θ_i – threshold value.

The specific form of the double threshold model is as follows:

$$\ln ric_{it} = \alpha_{it} + \beta_1 \ln x_{it}(x_i £\theta_1) + \beta_2 \ln x_{it}(\theta_1 < x_i £\theta_2) + \\ + \beta_3 \ln x_{it}(x_i > \theta_2) + \beta_4 \ln urb_{it} + \beta_5 \ln ig_{it} + \\ + \beta_6 \ln rtf_{it} + \beta_7 \ln reo_{it} + \beta_8 \ln aml_{it} + \\ + \beta_9 \ln fae_{it} + \beta_{10} \ln rhc_{it} + \mu_i \quad (14)$$

When there are more thresholds, the corresponding model can be obtained by expanding according to Equations (13) and (14).

Source of data

Because of constraints in the availability of certain data variables, we used panel data from 30 provinces,

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regions and municipalities in China spanning 2006 to 2021, excluding Hong Kong, Macao, Taiwan and Tibet. The sample data were derived from various national statistical yearbooks covering rural development (China Rural Statistical Yearbook 2007–2022), science and technology (China Science and Technology Statistical Yearbook 2007–2022), macro-economic indicators (China Statistical Yearbook 2007–2022), finance (China Financial Yearbook 2007–2022), leisure agriculture (China Leisure Agriculture Yearbook 2007–2022) and the tertiary sector (China Tertiary Industry Statistical Yearbook 2007–2022), along with primary data from the National Greenhouse Data System. To ensure data continuity, we estimated missing values through an appropriate interpolation technique and adjusted price-related numbers for inflation by using the consumer price index standardised to the year 2006.

RESULTS

Benchmark equation

In this study, we used the ordinary least squares method to estimate the benchmark equation, conducting regressions for four sets of models corresponding to the four core independent variables, and Table 3 reports the estimation results. The estimated parameters for *asta*, *aka* and *ata* were all positive and significant at the 1% level, indicating that these core independent variables had a significant positive effect on the dependent variable. An increase in their levels can promote the progress of the dependent variable. The estimated parameter for the *iakt* was negative and significant at the 5% level, indicating a significant negative effect on the dependent variable. Because the benchmark equation did not consider the endogeneity problem, the effect of these four core independent variables on the dependent variable needed to be verified further by means of the IV-2SLS method.

Endogeneity test

The reasons for the endogeneity issue in this study are as follows: First, there is the issue of reverse causality, where there is a two-way relationship between the dependent and independent variables. On the one hand, the independent variables affect the dependent variable, but on the other hand, the dependent variable can also exert a reverse influence on the independent variables, driving them to optimise, adjust or even undergo disruptive innovation. Second, there is omitted variable bias. Al-

Table 3. OLS estimation outcomes

Factor	Model 1	Model 2	Model 3	Model 4
asta	0.1342***	–	–	–
aka	–	0.0664***	–	–
ata	–	–	0.1300***	–
iakt	–	–	–	–0.0589**
urb	0.3098**	0.5566***	0.2924**	0.1922
ig	–0.2743**	–0.4256***	–0.2465*	–0.3863***
rtf	0.0368	0.0197	0.0332	0.0576***
reo	0.0456**	0.0229	0.0516***	0.0790***
aml	0.1872***	0.1603***	0.1659***	0.1471***
fae	–0.0732	–0.3988***	–0.0760	–0.5258***
rhc	-0.9856***	–0.6278***	–1.0491***	–0.6785***
c	–1.1557*	–1.2905**	–0.9659	–1.7141***
R^2	0.7691	0.6367	0.7686	0.6645
F	43.6000	58.2000***	43.4800***	29.4500***

*, **, *** significance level at 10, 5 and 1%, respectively; OLS – ordinary least square; *asta* – agricultural science and technology innovation; *aka* – agricultural knowledge innovation; *ata* – agricultural technology innovation; *iakt* – agricultural knowledge innovation and technology innovation convergence; *urb* – urbanisation level; *ig* – urban rural income gap; *rtf* – rural traffic level; *reo* – economic openness; *aml* – agricultural mechanisation level; *fae* – financial support for agriculture; *rhc* – rural human capital level

Source: Author's own calculations

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though a certain number of control variables are considered in the equation, some variables cannot be effectively proxied and thus are not included in the equation because of limitations such as data availability. Third, there is measurement error. In this research, we calculated the proxy variables for the dependent and independent variables, which may involve some degree of measurement error, leading to deviations from the actual values. For these reasons, it was necessary to conduct an endogeneity test on the baseline equation to obtain consistent and asymptotically efficient estimation results.

In this study, we selected strict exogenous variables from social space as instrumental variables to enter into the equation. The selected instrumental variables included the distance from provincial capitals to coastal ports calculated by longitude and latitude and the distance from provincial capitals to scientific and technological innovation centres (Beijing, Shanghai, Shenzhen) with global influence in China calculated by highway distance.

The IV-2SLS serves to analyse the endogenous nature of the equations. Table 4 reports the estimation results and shows that the equations successfully met

Table 4. IV-2SLS estimation outcomes

Factor	Model 1	Model 2	Model 3	Model 4
asta	0.0369***	–	–	–
aka	–	0.0267*	–	–
ata	–	–	0.0276*	–
iakt	–	–	–	0.0211
urb	0.3619*	0.3825*	0.3487*	0.2936
ig	–0.5492***	–0.5309***	–0.6426***	–0.6328***
rtf	–0.0015	0.0061	0.0033	0.0028
reo	0.0225	0.0199	0.0170	0.0081
aml	0.0542	0.0529	0.0575	0.0511
fae	–0.1493***	–0.1555***	–0.1433**	–0.1628***
rhc	1.1112**	1.1522**	1.0838**	0.9917*
LM	52.5130***	75.9260***	72.6270***	60.2600***
Wald *F*	137.3340***	34.4190***	161.2920***	37.0500***
Hansen	0.0350 (0.8515)	3.3180 (0.1903)	4.0810 (0.1300)	4.3660 (0.1127)

*, **, *** significance level at 10, 5 and 1%, respectively; (.) is the *P*-value of Hensen's test; IV-2SLS – instrumental variables – two-stage least squares; *asta* – agricultural science and technology innovation; *aka* – agricultural knowledge innovation; *ata* – agricultural technology innovation; *iakt* – agricultural knowledge innovation and technology innovation convergence; *urb* – urbanisation level; *ig* – urban rural income gap; *rtf* – rural traffic level; *reo* – economic openness; *aml* – agricultural mechanisation level; *fae* – financial support for agriculture; *rhc* – rural human capital level; *LM* – Kleibergen-Paap LM statistics

Source: Author calculated this based on the IV-2SLS model

Table 5. Threshold effect test

Equation	Original hypothesis	Alternative hypothesis	*F*-value	*P*-value	Threshold for statistical significance (%)		
					1	5	10
asta	one-threshold model	two-threshold model	21.510***	0.000	4.687	–2.444	–4.776
aka	one-threshold model	two-threshold model	51.596***	0.000	7.069	4.324	2.600
ata	one-threshold model	two-threshold model	13.069**	0.054	30.066	13.574	8.971
iakt	one-threshold model	two-threshold model	7.3690***	0.004	6.907	4.911	3.555

*, **, *** significance level at 10, 5 and 1%, respectively; *asta* – agricultural science and technology innovation; *aka* – agricultural knowledge innovation; *ata* – agricultural technology innovation; *iakt* – agricultural knowledge innovation and technology innovation convergence

Source: Author calculated this based on the threshold effect test

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the criteria of the relevant tests, confirming the validity of the chosen instrumental variables.

The estimated parameters of the key independent variables – *asta*, *aka* and *ata* – were all significantly positive, which, respectively, validate H_1, H_2 and H_3. This finding demonstrates that the development of these factors plays a crucial driving role in the dependent variable, implying that China, in particular, should emphasise their importance and critical role in advancing rural industrial development.

After addressing endogeneity, the estimated parameter for the *iakt* turned positive but did not pass the significance test. This finding suggests a positive relationship between this variable and the dependent variable, but its effect remains insufficient. The possible reason lies in the limited interaction efficiency between agricultural knowledge advancement and agricultural technology advancement, leading to a low conversion rate between the two. Consequently, the weak connection between the two fails to generate a significant effect on rural industrial incorporation.

Non-linear analysis

Furthermore, we applied the threshold panel model to explore the non-linear associations between key independent variables and the dependent variable. The panel threshold regression equation was formulated by incorporating *asta, aka, ata* and *iakt* as both predictors and threshold determinants.

Using the bootstrap method, we derived the *F*-value for the threshold effect test and the corresponding critical values after 500 repeated resampling iterations. Table 5 reports the test results, showing that the double threshold *F*-statistics for all equations were significant at at least the 95% level. This finding indicates the presence of double threshold effects

Table 6. Panel threshold model estimation outcomes

Factor	Model 1	Model 2	Model 3	Model 4
asta < 8.680	0.0676***	–	–	–
8.680 ≤ *asta* < 18.516	0.0923***	–	–	–
asta ≥ 18.516	0.1153***	–	–	–
aka < 9.490	–	0.1213***	–	–
9.490 ≤ *aka* < 13.029	–	0.0972***	–	–
aka ≥ 13.029	–	0.0732***	–	–
ata < 10.486	–	–	0.2078***	–
10.486 ≤ *ata* < 11.592	–	–	0.1833***	–
ata ≥ 11.592	–	–	0.1726***	–
iakt < −1.001	–	–	–	0.0198
−1.001 ≤ *iakt* < −0.856	–	–	–	0.1042**
iakt ≥ −0.856	–	–	–	0.0059
urb	0.3386***	0.9091***	0.3908***	0.1429
ig	−0.3198*	0.0267	−0.2530*	−0.2012
rtf	−0.1399***	−0.0242	0.0734*	−0.0271
reo	0.0984***	0.1014***	0.0733***	0.0562**
aml	0.1992***	0.0718*	−0.0417	0.0346
fae	−0.3662***	−0.2554***	−0.2427***	−0.1724***
rhc	1.2597***	−0.7331***	1.3311***	2.0105***
c	−3.7108***	−0.6953	−7.0669***	−5.2913***
R^2	0.5856	0.5587	0.6703	0.3966
F	36.8300***	35.2900***	64.7800***	22.2900***

*, **, *** significance level at 10, 5 and 1%, respectively; *asta* – agricultural science and technology innovation; *aka* – agricultural knowledge innovation; *ata* –agricultural technology innovation; *iakt* – agricultural knowledge innovation and technology innovation convergence; *urb* – urbanisation level; *ig* – urban rural income gap; *rtf* – rural traffic level; *reo* – economic openness; *aml* – agricultural mechanisation level; *fae* – financial support for agriculture; *rhc* – rural human capital level

Source: Author calculated this based on the panel threshold model

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between the core independent variables and the dependent variable. On the basis of these test results, we selected the double threshold effect model for regression analysis.

Table 6 reports the regression estimation results, where the estimated parameters for the key independent variables – *asta*, *aka* and *ata* – were significantly positive across the three intervals defined by two threshold values. This finding indicates that the threshold variables had positive non-linear effects on the dependent variable within each threshold interval, further validating H_1, H_2 and H_3 on the non-linear level. Although the estimated parameters were significantly positive in all threshold intervals, these threshold variables exhibited noticeable volatility across different intervals. Specifically, the estimated parameters for asta showed an increasing trend across the three intervals, with its positive effect on the dependent variable reaching its peak in the third interval. In contrast, the estimated parameters for *aka* and *ata* showed a decreasing trend, with their positive effects on the dependent variable being greatest in the first interval. This finding suggests that there were differences in the effects of these three core independent variables on the dependent variable and that there is still considerable room for improvement in the driving effects of *aka* and *ata*.

The regression parameters for *iakt* were positive across the intervals defined by two threshold values, but reached the 95% significance level only in the second interval. This finding aligns with the IV-2SLS estimation results, further emphasising that the effect of this variable on the development of the dependent variable depended on certain preconditions.

On the basis of this analysis, we can conclude that, for China, it is essential to establish a sound mechanism and external environment to unleash further the driving effects of agricultural science and technology advancement and its components on rural industrial incorporation.

DISCUSSION

Agricultural science and technology advancement and the progress of rural industrial incorporation are highly relevant modern topics. There is an inherent theoretical connection between the two, and examining their relationship in practice also holds significant real-world importance. In this study, we used China as a case study and, drawing on the breakdown of agricultural science and technology advancement, we incorporated its decomposed variables into the same analytical framework. On the basis of theoretical analysis, we further conducted an empirical analysis of the effect of these variables on rural industrial incorporation, considering both linear and non-linear perspectives.

The results of our analysis demonstrated, on the whole, that progress in agricultural science and technology plays a crucial role in fostering the progress of rural industrial incorporation. These findings align with those of Yao et al. (2024) and Jiao and Liu (2022), as well as with the views presented by Cao et al. (2024). This alignment of results is mainly attributed to the recent breakthroughs and progress made in various fields of agricultural science and technology advancement within China, which have effectively accelerated the transformation of Chinese agricultural technology, positioning agricultural science and technology advancement as a key factor in building a strong agricultural nation (Lan 2024). Examination of the decomposed indicators indicated that advancement in agricultural knowledge and technology played a crucial role in fostering the progress of rural industrial incorporation. The effect of agricultural knowledge advancement on this incorporation development is consistent with the theoretical perspectives of Yan and He (2013). The findings on the effect of innovation in agricultural technology on the integrated development of rural industries showed a certain degree of consistency with the research results of Nie et al. (2020) and Wang et al. (2024). In addition, the integration of agricultural knowledge advancement and technology advancement contributed to the progress of rural industrial incorporation, but this effect was not significant.

We believe the root cause may lie in the low level of conversion from agricultural knowledge to technological innovation. This issue may stem from the disconnect between the agricultural knowledge system and technological applications, the low level of alignment between the agricultural technology promotion system and market mechanisms, constraints related to the intellectual property system of innovation outcomes and the lag in the evaluation system for technological advancements.

We further relaxed the assumption of linearity and explored how agricultural science and technology advancement, along with its decomposed variables, influenced the progress of rural industrial incorporation through a non-linear approach. In this study, we found that, overall, the estimated coefficients of agricultural science and technology advancement in different intervals showed an increasing trend, reaching their maxi-

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mum effect in the third interval. This finding implies that the effect of agricultural science and technology advancement on the progress of rural industrial incorporation within the sample area was experiencing a gradual increase. On the one hand, this increase may be attributed to the rapid development of agricultural science and technology advancement within China, which has lowered unit costs and realised economies of scale through cumulative effects; on the other hand, the increase benefits from the support of relevant policies and the promotion of improved infrastructure. At the level of decomposed indicators, the values for agricultural knowledge advancement and agricultural technology advancement across the three intervals exhibited a decreasing trend, suggesting that their influence on the progress of rural industrial incorporation was experiencing a marginal decrease. From one viewpoint, this decrease may be due to the diminishing marginal effects of agricultural knowledge advancement and agricultural technology advancement themselves, as well as limitations in their spillover effects; from another viewpoint, the decrease may be ascribed to the relatively low level of progress of rural industrial incorporation in China (Li and Xu 2022), which restricts the capacity to absorb innovation outcomes. The estimated coefficients of the integration of agricultural knowledge advancement and technology advancement in the three intervals were all positive, but only in the second interval did they pass the significance test, meaning that the significant effect of these independent variables on the dependent variable in China can be realised only under more stringent conditions at the current stage. This finding further highlights the need to pay sufficient attention to the negative effect caused by the low level of conversion from agricultural knowledge advancement to technological innovation and to seek appropriate solutions to address the causes of this issue.

This study has two main limitations. First, the information we presented here was sourced from relevant yearbooks and data obtained from websites. However, because of factors such as sample selection, data omissions, measurement errors, subjective biases of investigators or respondents, data entry errors and inappropriate statistical methods, the data may contain a certain degree of bias, potentially affecting the research conclusions. Second, in this study, we examined China as an example, with the analysis results being influenced by factors such as China's economic development level, policy environment, social culture and institutional framework. Consequently, the findings exhibit strong regional dependency, which imposes certain limitations on their applicability and generalisability.

Further development of this research mainly involves four areas. In the first place, although this study involved decomposed agricultural science and technology advancement, because of data availability constraints, some decomposed indicators (such as institutional innovation and other factors) were not included in the analysis, which warrants further improvement in future research. In the second place, the proxy variables for the integration of agricultural knowledge advancement and technology advancement have room for optimisation, and future research could explore better proxy variables. In the third place, consideration should be given to using diversified methods for a more comprehensive endogeneity analysis along multiple dimensions, including improving instrumental variables and using techniques such as propensity score matching to test for potential bias issues due to sample selection. In the fourth place, focussing on spatial effects, future research could involve methods such as spatial panel Durbin models to examine the spatial effect of agricultural science and technology advancement and its decomposed indicators on the progress of rural industrial incorporation.

CONCLUSION

In this study, we used China as a case study and analysed the influence of agricultural science and technology advancement and its decomposed variables on rural industrial incorporation from both linear and non-linear perspectives. The study results showed the following:

From a linear perspective, the coefficients for agricultural science and technology advancement, agricultural knowledge advancement and agricultural technology advancement were all positive and statistically significant. These three variables play a crucial role in advancing the progress of rural industrial incorporation. The coefficient for the integration of agricultural knowledge advancement and technology advancement had a positive value, although it did not meet the significance threshold, suggesting a correlation between this variable and the progress of rural industrial incorporation. However, this variable had not yet had sufficient influence on the dependent variable.

From a non-linear perspective, the estimation coefficients of agricultural science and technology advancement, agricultural knowledge advancement and agricultural technology advancement were significantly positive across different intervals. However,

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the fluctuation characteristics varied across intervals, and the driving effects of agricultural knowledge advancement and agricultural technology advancement on rural industrial incorporation had significant potential for enhancement, so future efforts should focus on continuous and systematic optimisation in areas such as development planning, policy support, financial security and talent cultivation. The estimated coefficients for the integration of agricultural knowledge advancement and technology advancement were positive across different intervals, but only in the second interval did they reach statistical significance, suggesting that the current effect of agricultural knowledge advancement and agricultural technology advancement on promoting the progress of rural industrial incorporation in China depends on specific conditions.

Policy implications

Given the conclusions of this study, maintaining and further enhancing the effective driving effect of agricultural science and technology advancement, along with its decomposed variables, on the progress of rural industrial incorporation hinges on coordinated efforts in terms of both supply and demand. In terms of supply, the focus should be on systematically optimising the decomposed indicators. Regarding demand, the emphasis should be on improving the ability of rural industrial incorporation to absorb innovation achievements. Accordingly, we present the following policy implications.

Enhance the progress of agricultural knowledge advancement. The first approach is to improve the development of agricultural science programmes, dynamically grasping the situation of agricultural science professional construction through regular subject evaluations, and thus carry out targeted improvement and filling in gaps. Special attention should be given to basic disciplines. The second is to increase the emphasis on soft science while maintaining the degree of emphasis on advancements in agricultural hard technologies to improve the balance between 'soft' and 'hard'. Third, coordinate the connection between agricultural knowledge advancement content and national goals and guide their alignment through the execution of key national initiatives. Fourth, establish a sound environment for the main entities of innovation, continue to maintain and increase investment in agricultural knowledge advancement and ensure that these entities have sufficient funding to carry out research; progressively raise the treatment of the main entities of innovation, enabling them to focus on scientific research. Fifth, on the basis of information technology, actively promote the digitisation and sharing of agricultural knowledge innovation through the establishment of agricultural knowledge databases, agricultural knowledge service platforms and other initiatives.

Improve agricultural technology advancement capabilities. First, it is essential to establish a favourable external environment for agricultural technology advancement. On the one hand, this requires optimising the policy environment and leveraging policy tools to promote agricultural technological advancement further. On the other hand, the government should focus on highly innovative enterprises and increase investment in technology enterprises' innovation activities. In addition, efforts should be made in finance, information and intellectual property to enhance and improve the innovation market mechanism. Second, fostering a conducive internal ecosystem for agricultural technology advancement is crucial. This effort involves cultivating a corporate culture that encourages innovation, making the pursuit of innovation-driven development a core value and a driving force for agricultural technological progress. Furthermore, it is necessary to ensure a continuous input of essential resources such as capital and talent to sustain technological innovation. In addition, enterprises should actively explore innovation models that align with their specific circumstances, striking a balance among independent innovation, imitative innovation and collaborative innovation to enhance the efficiency of innovation investment.

Strengthen the integration of agricultural knowledge advancement and technology advancement. First, a collaborative innovation mechanism should be established to enhance the efficiency of knowledge transformation into technology. This innovation requires creating a synergy-driven framework in which the government provides guidance, universities and research institutes take the lead and enterprises participate deeply, thereby accelerating the conversion of agricultural knowledge advancement into agricultural technology advancement. Second, intermediary platforms should be leveraged to facilitate interaction and integration between agricultural knowledge innovators and agricultural technology innovators. This interaction and integration would enable effective exchange and transformation of innovation outcomes, unlocking the latent value of knowledge innovation. Third, by strengthening market orientation and enhancing

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the diversification of stakeholders, the agricultural technology extension system's alignment with market mechanisms could be effectively improved. Fourth, the intellectual property protection and management mechanisms should be refined to eliminate institutional constraints on the ownership of innovation achievements. Fifth, a comprehensive and scientifically sound evaluation system for technological achievements should be established and improved.

Enhance the acceptance ability of rural industrial incorporation for agricultural science and technology advancement. First, continue to enhance the educational standard and cultural literacy of key actors in rural industrial incorporation. This enhancement can be achieved through training and continuing education, improving the ability of these key actors to learn from innovations and laying a solid foundation for better adoption of these innovations. Second, enhance collaboration with educational and research establishments by leveraging the science commissioner system, which will help establish continuous and stable channels for technology transfer among universities, research institutions and key actors in rural industrial integration. Third, accurately identify the specific innovation needs of different stakeholders in rural industrial incorporation and promote more aimed agricultural technology innovations based on demand-oriented principles. Fourth, actively develop diversified models of rural industrial incorporation to enhance the variety of application scenarios for agricultural science and technology advancement, as well as to stimulate greater demand.

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