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The impact of industrial agglomeration on new quality productive forces enhancement in China's pig farming industry

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Enhancing the development of new quality productive forces (NQPF) has become a critical pathway for overcoming the "low-end lock-in" of the pig industry and achieving high-quality growth. Based on panel data from 31 Chinese provinces spanning 2011 to 2022, this study employs benchmark regression models, mediation effect models, and threshold effect models to empirically analyze the impact of industrial agglomeration (AGG) on the enhancement of new quality productive forces in the pig farming industry (NQPP) and its underlying mechanisms. The findings revealed that (1) AGG significantly enhances NQPP, and this conclusion remains robust across various robustness tests. (2) Industrial structure upgrading (ISU) serves as the intrinsic driving force behind the positive effect of AGG on NQPP enhancement. (3) The spillover effects of AGG on NQPP enhancement exhibit a significant non-linear characteristic of "increasing marginal effects". (4) The impact of AGG on NQPP enhancement varies across regions. The promotional effect is more pronounced in regions rich in resources and with strong development potential. Accordingly, the policymakers should carefully consider regional factor endowments and production capacities when formulating differentiated policy measures tailored to local conditions. Additionally, efforts should be made to strengthen the integration of the pig industry chain and promote technological innovation, thereby facilitating the industry's transition toward intensification, efficiency, and sustainability.

Keywords Pig farming industry, Industrial agglomeration, New quality productive forces, Industrial structure upgrading, China

Abbreviations

NQPF	New quality productive forces
NQPP	New quality productive forces in the pig farming industry
AGG	Industrial agglomeration
ISU	Industrial structure upgrading
UR	Urbanization rate
AE	Level of development of the agricultural economy
CA	Comparative advantage index
FR	Food resources
WR	Water resources
PL	Production layout
ER	Environmental regulation

As a key pillar of China's agriculture, the pig industry has long played a vital role in ensuring food security and driving rural economic development. In recent years, with the evolving dietary habits of the population and increasing academic focus on agricultural modernization and sustainability, large-scale and green farming practices have gained significant attention[1]. In this context, the pig industry is transitioning from extensive to intensive and modernized production methods. Particularly in light of the "dual carbon" goal, the adoption of green, safe, and efficient production techniques has become central to the industry's upgrading. In response, the People's Republic of China (PRC) has introduced several policy initiatives, including the "Opinions of the General Office of the State Council on Promoting High-Quality Development of the Animal Husbandry Sector" (2020)

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and the "National Animal Husbandry Development Plan (2021–2025)" (2021), which also explicitly advocate for green development in animal husbandry while improving the quality and safety standards of livestock products. However, in terms of production practices, the development of the pig farming industry continues to face numerous challenges, such as high production costs, low breeding efficiency, insufficient industrial integration, limited automation, and high labour intensity[2,3]. These issues primarily stem from the fact that traditional pig farming is a labour-intensive industry characterized by a low-skilled workforce, limited labour availability, and inefficient utilization of production materials. Additionally, the uncertainty and risks associated with disease transmission further heighten the vulnerability of the pig farming industry's development. Clearly, the growth is not only constrained by the scarcity of traditional labour and land resources but also by stringent ecological safety requirements and environmental regulations. These factors make the pursuit of high-quality, sustainable development in pig farming particularly complex and challenging.

In September 2023, at a symposium on the comprehensive revitalization of Northeast China, President Xi Jinping introduced the theoretical concept of "new quality productive forces" (NQPF) for the first time. Subsequently, both the Central Rural Work Conference in 2024 and the No. 1 Central Document in 2025 emphasized the importance of developing NQPF in agriculture based on local conditions. NQPF in agriculture serves as a core driving force behind agricultural modernization[4], with a substantial increase in total factor productivity (TFP) serving as the key indicator[5]. Centred on technological innovation, it promotes sustainable development through the innovative allocation of production factors, industrial transformation, and the reform of traditional production methods. Building on this foundation, this study argues that new quality productive forces in the pig farming industry (NQPP) as an efficient, green, and sustainable form of productivity jointly constituted by new-quality labourers, new-quality objects of labour, and new-quality means of production. It is driven by agricultural technological innovation, fostering advanced productive forces through the innovative allocation of production factors and deep industrial transformation and upgrading. These forces facilitate the transition of the pig industry from traditional farming models to modernization, intelligence, and sustainability. Therefore, accelerating the cultivation and adoption of NQPP may be a crucial pathway for fostering high-quality development and establishing a modernized pig farming industry system.

Industrial agglomeration (AGG), as a distinctive spatial integration of production factors, leverages geographical concentration and industrial interconnectedness to effectively reduce production costs, drive technological innovation, and promote industrial upgrading. It achieves these outcomes by optimizing resource allocation, deepening labour division, and facilitating the creation and dissemination of green knowledge[6]. Consequently, AGG presents new opportunities for traditional industries to transition toward modern, high-efficiency, high-quality, and sustainable production methods. Numerous scholars have explored the impact of AGG on sustainable industrial development, including studies on AGG and corporate digital transformation[7], supply chain resilience[8], green TFP[9]. Although the aforementioned studies have provided preliminary evidence on how AGG influences the development of NQPF, research in the specific context of the pig industry remains notably insufficient. Existing research has predominantly focused on secondary and tertiary industries[10], lacking systematic investigation into the agglomeration effects in agriculture—particularly in the pig industry. This gap limits the understanding of the unique characteristics of the pig industry. On the other hand, while some scholars have explored how AGG enhances TFP through pathways such as technological innovation[11], human capital structure[12], and industrial structure optimization[9], the mediating mechanism by which AGG influences NQPF enhancement through industrial structure upgrading (ISU) remains insufficiently constructed and empirically validated. Against the backdrop of "NQPF" being formally proposed and incorporated into China's national strategic agenda, this study seeks to address the following research questions: Does AGG truly enhance the NQPP within the sector? Does ISU play a mediating role in this process? Furthermore, does the role of AGG in enhancing NQPP vary across different regions and different levels of technological innovation?

This study examines the pig industry through a comprehensive analytical framework. First, we measure AGG using the location entropy index and assess NQPP through Principal Component Analysis (PCA). Subsequently, we employ three econometric approaches to investigate the relationship and underlying mechanisms between AGG and NQPP: baseline regression models, mediation effect models, and panel threshold models. To address potential endogeneity issues, we implement rigorous correction methods including IV method and two-step system GMM estimation. This multi-method strategy significantly enhances the reliability of our findings, with robustness checks confirming the validity of our research results. This research carries significant theoretical and practical implications. It contributes to improving industry toward greater efficiency, enhancing quality, reducing carbon emissions, and promoting modernization and sustainable development in pig farming.

Literature review

The economic phenomenon of AGG was first brought to attention by the American military strategist, politician, and diplomat George Marshall. Since then, it has been widely discussed in academic circles. Scholars have sought to apply AGG to the pig industry, exploring various aspects such as the reasons for its formation[13], driving factors[14], methods for measuring the degree of AGG[15], and the effects of AGG[16]. First, regarding the formation of AGG, scholars contend that production specialization, external incentive effects, and the sharing and dissemination of information can effectively reduce production and transaction costs for pig farming enterprises, thereby improving resource utilisation efficiency[17]. Second, in examining the driving factors of AGG, some scholars argue that AGG is influenced by comprehensive factors, such as natural resource conditions[13], technological levels[14], market consumption potential[18], transportation conditions[19], climate conditions[20], and policy support[21]. Additionally, some scholars consider the linkage between upstream and downstream industries a key driver of AGG formation[22]. Moreover, in terms of measuring AGG, scholars commonly employ the location entropy index[23], the Gini coefficient[24], and the industrial concentration index[25]. Finally, with regard to the effects of AGG, Zhang et al.[26] found that AGG and ISU exert significant non-linear effects on agricultural sustainable

development. Other studies indicate that AGG in livestock farming exhibits apparent threshold effects and distinct characteristics in relation to economic growth[27,28].

NQPF serves as a key driver in promoting sustainable industrial development in response to the demands of the economic era[29]. Agriculture is a crucial domain for NQPF development[30], as its advancement plays a fundamental role in implementing the rural revitalization strategy, strengthening the agricultural sector, and achieving the modernization of agriculture and rural areas[31]. However, research on the development of NQPP remains relatively limited. Given that the pig industry is part of the agricultural sector, this study explored the concept of NQPF in agriculture. Existing scholarly research on NQPF in agriculture primarily focuses on theoretical discussions, the development of evaluation systems, and measurement approaches. In terms of theoretical discussions, scholars have primarily examined the connotation of NQPF[32], its formation logic[33], and its development pathways in agriculture[34,35]. Regarding the evaluation and measurement of NQPF in agriculture, two main approaches are prevalent. The first approach, based on the theory of productivity elements, evaluates NQPF through three dimensions: new-quality labourers, new-quality means of production, and new-quality objects of labour[4,29]. The second approach, grounded in the characteristics of NQPF, assesses it through three dimensions: technological productivity, green productivity, and digital productivity[36]. In terms of measurement methodologies, existing studies predominantly rely on entropy methods for assessing NQPF in agriculture[4,37].

Although the academic community has extensively explored AGG and NQPF in agriculture separately, few studies have integrated both into a unified analytical framework. However, a fundamental indicator of enhancing NQPF is a significant improvement in TFP. The literature most relevant to this study primarily unfolds from two perspectives: ①Theoretical linkages between AGG and NQPF. Current theoretical perspectives posit an inherent connection between AGG and the development of NQPF[38]. As a spatial-economic phenomenon characterized by the dense integration of production factors—including resources, technologies, institutions, and organizational structures—AGG may serve as a critical catalyst for NQPF enhancement in agricultural sectors. Yuan et al.[39] and Rosenthal[13] pointed that the spatial concentration of industries, enhanced inter-firm linkages, and strengthened social networks inherent in agglomerations improve resource allocation efficiency and expand production possibility frontiers. These effects facilitate the emergence of NQPF, including new-quality labourers, new-quality objects of labour, and new-quality means of production[40]. Liu et al.[41] agreed that agglomeration-induced economies of scale, intensified market competition, and knowledge spillover effects collectively stimulate enterprise innovation capacity, thereby generating the technological foundation essential for NQPF. Li et al.[42]found that AGG provides an experimental environment for institutional reforms and organizational evolution, establishing the necessary governance frameworks to support sustained NQPF development. ②The relationship between AGG and agricultural TFP. The academic community holds divergent perspectives regarding the impact of AGG on agricultural TFP. A substantial body of research demonstrates that AGG exerts significant positive effects on agricultural TFP growth[43,44]. However, other scholars characterize AGG as a "double-edged sword," arguing that while it generates scale economies, it may simultaneously induce congestion effects, resulting in a non-linear relationship with agricultural TFP[45]. Notably, empirical evidence suggests that the nature of this relationship exhibits considerable regional heterogeneity, being highly contingent on the specific characteristics of the sampled areas[46]. Furthermore, several scholars have investigated the transmission mechanisms through which AGG affects agricultural TFP[11], with technological innovation, industrial restructuring, human capital accumulation, and environmental regulation identified as critical pathways for TFP enhancement[47,48].

In summary, existing research provides valuable insights into the relationship between AGG and the development of NQPP. However, it has yet to establish a clear theoretical framework explaining this relationship or reach a consensus on whether and through what pathways AGG promotes the development of NQPP. To address these gaps, this study utilized panel data from 31 provinces in China from 2011 to 2022, incorporating the unique characteristics of the pig farming industry. It constructed a comprehensive evaluation system to measure the development level of NQPP across three dimensions: new-quality labourers, new-quality objects of labour, and new-quality means of production. A bidirectional fixed-effects model was employed for empirical analysis to examine the impact of AGG on NQPP development. Furthermore, from the perspective of ISU, a mediation effect model was applied to explore the internal mechanisms through which AGG enhances NQPP. Based on this, the potential marginal contributions of this study are as follows. First, building on existing research, this study employs the location entropy index to measure AGG and adopts the PCA method to assess NQPP, revealing their spatiotemporal evolution characteristics and impact relationships, thereby providing new empirical evidence for related studies. Second, by empirically analysing the impact of AGG on NQPP enhancement, this study addresses the research gap concerning their relationship, contributing to the theoretical framework in this field. Third, from the perspective of ISU, this study elucidates the intrinsic mechanisms and pathways through which AGG influences the enhancement of NQPP within a unified framework, thereby deepening the theoretical understanding of their relationship. Fourth, by conducting a heterogeneity analysis of AGG's impact on NQPP enhancement across dimensions such as different regional conditions and varying levels of technological innovation, this study offers policy recommendations for promoting NQPP enhancement and fostering the high-quality development of the pig farming industry.

Theoretical mechanisms and research hypotheses

Before examining the logical relationship between AGG and NQPP in detail, it is essential to define these concepts. Based on the aforementioned definitions, NQPP represents an advanced form of productivity driven by agricultural technological innovation. It is achieved through the innovative allocation of production factors and the profound transformation and upgrading of the industry. NQPP not only focuses on improving the production efficiency and economic benefits of pig farming but also emphasizes the integration of the pig industry chain, the application of innovative technologies, and the environmental protection and sustainability

of the entire industry. Additionally, it seeks to ensure product safety, strengthen industrial competitiveness, and promote a balanced coexistence between the natural environment and socioeconomic development. AGG refers to the concentration of interrelated upstream and downstream enterprises within a specific geographical area, forming an industrial cluster driven by interdependence, complementarity, and mutual reinforcement. This clustering optimizes resource allocation and industrial coordination, ultimately enhancing the overall competitiveness and sustainable development capacity of the entire industry. This section explores the intrinsic mechanisms through which AGG influences the enhancement of NQPP from three perspectives: direct effects, indirect effects, and non-linear spillover effects. Furthermore, it proposes relevant hypotheses.

Direct impact of AGG on NQPP enhancement

The theory of AGG posits that the concentration of enterprises within the same or related industries within a specific geographical region forms an industrial cluster[49], thereby enhancing economic efficiency, improving production efficiency, fostering innovation, and significantly increasing product quality[12]. In the context of the pig farming industry, AGG functions as an effective resource integration mechanism that facilitates the development of NQPP through various channels, including economies of scale, competitive effects, innovation effects, and knowledge spillovers. The advancement of NQPP is not only essential for addressing challenges such as low skill levels among traditional labourers and optimizing the efficiency of labour objects and production means[50] but also serves as a necessary pathway for promoting the high-quality development of the pig industry.

First, AGG enhances the skills of pig farming labourers through the "knowledge spillover effect" and the "learning effect". On one hand, agglomeration areas attract numerous professionals and management experts. The "advanced resources" embedded within this clustering effect serve as the most direct driving force for enhancing NQPP. On the other hand, communication and collaboration among farming enterprises facilitate the absorption and generation of knowledge[51]. Within these agglomeration areas, pig farming enterprises gain easier access to the latest breeding technologies and management practices through participation in training programs, on-site visits, and technical seminars. Through practical experience and accumulated expertise, labourers master advanced breeding techniques and management concepts, thereby continuously improving their farming skills and professional competence[52], such as mastering and maintaining the operational procedures of intelligent farming equipment. This model not only accelerates knowledge acquisition and innovation but also enhances the overall quality of the labour force in the pig farming industry, thereby providing essential talent support for the advancement of NQPP.

Second, AGG enhances resource allocation efficiency through the economies of scale effect", facilitating the development of new quality means of production in the pig farming industry. Within agglomeration areas, enterprises benefit from shared infrastructure, logistics, and technical services, such as feed supply, veterinary care, logistics networks, and manure treatment technologies. This reduces spatial distances between upstream and downstream enterprises in the pig industry chain, research institutions, and service providers, fostering a highly coordinated and resource-complementary industrial ecosystem[53]. This large-scale production model not only enables pig farming enterprises to utilize various resources—including land, capital, technology, and skilled labour—more efficiently but also creates favourable conditions for the adoption, application, and continuous advancement of new quality means of labour in the industry. These include precision feeding systems, information management platforms, intelligent temperature control mechanisms, and automated slaughtering equipment.

Third, AGG enhances the pig farming industry through "innovation effects" and "competition effects". It fosters a conducive environment for technological advancements, encouraging farming enterprises to adopt new technologies, processes, and management strategies to enhance competitiveness, improve production efficiency, and elevate product quality[54]. For example, the integration of intelligent farming systems enables precise management, disease prevention, and nutritional regulation in pig farming. Smart environmental control systems mitigate heat stress in animals, enhancing their health and welfare. Additionally, automated manure removal systems improve water and air quality, contributing to ecological sustainability in farming operations. This competitive pressure drives the industry to transition from traditional farming models to environmentally friendly and intelligent farming practices, marking a significant leap in the traditional productivity of the pig farming industry. Therefore, this study propose the research Hypothesis 1:

H1 AGG positively promotes NQPP enhancement.

Indirect impact of AGG on NQPP enhancement: the role of ISU

According to the Petty–Clark Theorem, as economies develop, the labour force gradually shifts from low-value-added sectors to high-value-added sectors. ISU, serving as a new engine of economic growth, functions as both a "resource converter" and an "innovation driver"[55] and represents an intrinsic force in enhancing NQPF[56]. AGG has facilitated the concentration of resources—such as enterprises, talent, and technology—associated with pig farming within specific regions. This has optimized the industry's structure, reshaped its spatial distribution, and transformed traditional breeding models, thereby creating favourable conditions for the transformation and upgrading of the pig farming industry. Moreover, AGG has significantly contributed to the emergence of a new quality labour force, new quality objects of labour, and new quality means of production, ultimately driving the enhancement of NQPP. At the core of this process is innovation-driven development[57]. On one hand, the adoption of smart breeding technologies—such as biotechnology, information technology, automation, and intelligent systems—within the pig farming industry has not only provided a practical platform for labourers with innovative capabilities and practical expertise but has also played a crucial role in skill development. This, in turn, has become a key driving force behind NQPP enhancement. On the other hand, enterprises have expanded the upstream and downstream segments of the pig farming industry chain through ISU by developing high-value-added sectors, such as deep processing, brand marketing, and cold chain logistics. These efforts have fostered a diversified development landscape, improved market competitiveness, and unlocked new growth

opportunities for NQPP enhancement. Additionally, the dual forces of policy support and market mechanisms have established a strong foundation for NQPP enhancement. Therefore, this study proposes the following research hypothesis 2:

H2 AGG indirectly drives NQPP through ISU.

Non-linear spillover effects of AGG on NQPP enhancement

The new economic growth theory posits that the sustainability of economic growth arises from the cross-boundary flow of knowledge elements and the continuous advancement of technological systems. Within this theoretical framework, AGG, by facilitating the concentration and optimal allocation of resource elements, can significantly enhance industrial productivity, innovation capacity, and product quality, ultimately leading to comprehensive improvements in economic efficiency. In the pig industry, while the enhancement of NQPP is influenced by multiple interrelated factors, its core driving force lies in the optimization of industrial development models and the efficient allocation of resources. Research indicates that traditional household free-range farming is a major contributor to environmental pollution[58], as this model exacerbates conflicts between the industrial layout of animal husbandry and the carrying capacity of resources and the environment[59]. AGG facilitates the clustering of related enterprises within specific geographic regions, fostering technology diffusion, information sharing, and resource coordination[60], thereby providing critical support for ISU. However, in the early stages of AGG, the adoption of modern breeding technologies—such as automated feeding systems, environmental control mechanisms, and disease prevention strategies—requires substantial capital investment and a solid technological foundation. Simultaneously, large-scale farming imposes higher demands on management capabilities, necessitating professionals with expertise in modern breeding management. Consequently, the scale effect outweighs the technology and structural effects. Nevertheless, as breeding practices evolve and resource accumulation progresses, the influence of the technology effect and structural optimization gradually strengthens, eventually surpassing the economies of scale effect. This transformation not only drives the sustainable development of the pig industry but also significantly enhances NQPP[61]. Based on this, this study proposes the following research hypothesis 3:

H3 AGG may have a non-linear impact on NQPP enhancement.

Research design

Model construction

Benchmark regression model

To analyse the direct transmission mechanism of AGG in enhancing NQPP, the following basic model was constructed:

$$NQPP_{i,t} = \alpha_0 + \alpha_1 AGG_{i,t} + \alpha_2 Z_{i,t} + \mu_i + \sigma_t + \varepsilon_{i,t} \quad (1)$$

where i represents the region, t represents the year, NQPP represents new quality productive forces in the pig farming industry, and AGG represents pig farming industrial agglomeration. Z represents a set of control variables, μ denotes the fixed effect of the region, and δ signifies the fixed effect of time. α_0 is the intercept term, α_1 is the regression coefficient of the concentration of the pig farming industry—the primary coefficient of interest in this study—while α_2 is the regression coefficient of the control variable. Finally, ε represents the random disturbance term.

Mediation effect model

ISU refers to the process of industrial transformation, characterized by a shift from low value-added to high value-added production, low-technology to high-technology applications, low processing sophistication to high processing sophistication, low capital intensity to high capital intensity, and low labor productivity to high labor productivity. This transformation signifies the evolution of traditional industries from extensive production modes to intensive, refined, and modernised production methods. To examine whether ISU mediates the impact of AGG on NQPP enhancement, this study constructed the following mediation effect models:

$$M_{i,t} = \beta_0 + \beta_1 AGG_{i,t} + \beta_2 Z_{i,t} + \mu_i + \sigma_t + \varepsilon_{i,t} \quad (2)$$

where M represents the mediating variable; β_0 is the intercept terms; β_1 and β_2 are the regression coefficients of the corresponding variables in the model. The remaining coefficients are identical to those in Eq. (1).

Threshold effect model

To further explore the threshold effect of AGG on NQPP enhancement, this study used ISU as the threshold variable to examine the threshold effect on the enhancement of NQPP. The model was constructed as follows:

$$NQPP_{i,t} = \phi_0 + \phi_1 AGG_{i,t} \times I(Q_{i,t} \le X) + \phi_2 AGG \times I(Q_{i,t} > X) + \phi_3 Z_{i,t} + \mu_{i,t} + \varepsilon_{i,t} \quad (3)$$

where Q represents the threshold variable, X denotes the threshold value, and ϕ_0, ϕ_1, ϕ_2 and ϕ_3 are the coefficients and intercept terms of the corresponding variables, respectively. The remaining coefficients are identical to those in Eq. (1). The indicator function $I(\cdot)$ takes a value of 1 if the condition in the brackets is met and 0 otherwise.

Variable measurement and description

Measurement of the development level of NQPP

The explanatory variable in this study is NQPP. To objectively assess the comprehensive development level of NQPP across 31 provinces in China from 2011 to 2022, this study builds on the research of Huang et al.[4] and Lin et al.[30]. Drawing from their frameworks, it constructed a system of 17 sub-dimensional indicators categorized into three core dimensions: new-quality labourers, new-quality objects of labour, and new-quality means of production (Table 1). The PCA method is employed to calculate these indicators, yielding a comprehensive development level index for NQPP.

Figure 1 illustrates the changes in the comprehensive development level of NQPP across various regions of China from 2011 to 2022. The data indicate a steady overall improvement in NQPP development across all regions, with the most significant progress observed in 2021. Based on geographical divisions, this study categorized China's 31 provinces into seven regions: North China, Northeast China, East China, Central China, South China, Southwest China, and Northwest China. From a regional perspective, the comprehensive development level of NQPP in Southwest China, Central China, and Northeast China exceeds the national average. In contrast, the comprehensive development level of NQPP in East China, South China, Northwest China and North China is below the national average.

Measurement of pig farming industry agglomeration

The core explanatory variable in this study is AGG. To measure the development level of AGG, this study employed the location entropy index, drawing on the research of Xu et al.[23]. The location entropy index, as a sophisticated analytical tool, not only accurately captures the spatial distribution of geographical elements but also effectively accounts for differences in regional economic scale. It has been widely applied in various studies. The specific calculation formula is as follows:

$$AGG_{it} = \frac{P_{it}/A_{it}}{P_t/A_t}$$

where AGG_{it} represents the level of pig farming industry agglomeration in province *i* in year *t*, with higher values indicating a greater level of AGG. P_{it} and P_t represent the pig farming output value of province *i* and the national output value in year *t*, respectively. Similarly, A_{it} and A_t represent the livestock output value of province *i* and the national output value in year *t*, respectively.

Figure 2 illustrates the changes in AGG levels across different regions from 2011 to 2022. High-agglomeration areas are primarily concentrated in Central China, East China, South China, and Southwest China, while low-agglomeration areas are primarily found in Northwest China, North China, and Northeast China. This may be attributed to these regions' relatively underdeveloped geographic location, resource endowments, and transportation convenience.

Primary indicator	Secondary indicator	Tertiary indicator	Indicator interpretation	Attribute
New-quality labourers	Labour skills	Education level of workers	Average years of education for rural residents	+
		Labour skills training	Employees in the pig farming industry×(Number of rural workers trained ÷ Rural resident population)	+
	Labour efficiency	Per capita output value of the pig farming industry	Gross output value of live pigs ÷ Number of people employed in pig farming	+
	Labourer employment concept	Labour force level in the pig farming industry	Employment share of pig farming in rural population	+
New-quality objects of labour	Green environmental protection and pollution reduction	Total pollutant discharge from pig farming	Emissions of contaminants including chemical oxygen demand, total nitrogen, total phosphorus, copper, and zinc	−
		Carbon emission intensity of the pig farming industry	Total carbon emissions from pig farming ÷ Gross output value of live pigs	−
	New quality industry	Level of smart pig farming	Total mechanical power in pig breeding ÷ Total live pig inventory	+
		Development of animal husbandry	Share of livestock value ÷ added in gross agricultural output	+
New-quality means of production	Infrastructure	Rural road mileage	Total rural road mileage ÷ Rural resident population	+
	Energy consumption	Proportion of livestock intermediate consumption	Livestock intermediate consumption ÷ Total primary sector intermediate consumption	−
		Energy consumption in the pig farming industry	Total agricultural energy consumption ÷ Gross output value of live pigs	−
		Electricity consumption of pig farming	Rural electricity consumption ÷ Gross output value of live pigs	−
	Technological innovation	Number of animal husbandry technicians	Total of junior, intermediate, and senior animal husbandry technicians	+
		R&D investment in the pig farming industry	R&D expenditure × (Gross output value of live pigs ÷ Gross domestic product)	+
		Number of basic animal husbandry stations	Direct access	+
	Digital transformation of traditional industries	Rural digital inclusive finance index	Peking university digital inclusive finance index (2011–2022)	+
		Agricultural IOT technology application	Rural delivery routes	+

Table 1. Comprehensive index evaluation system for NQPP.

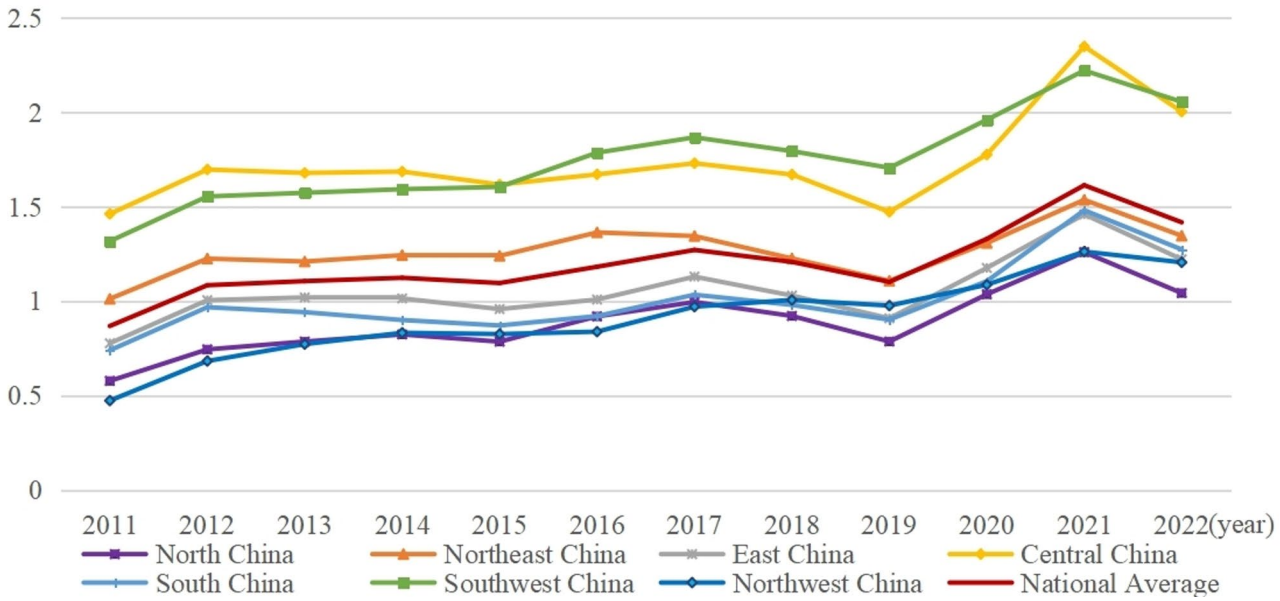

Fig. 1. Development level of NQPP in different regions from 2011 to 2022.

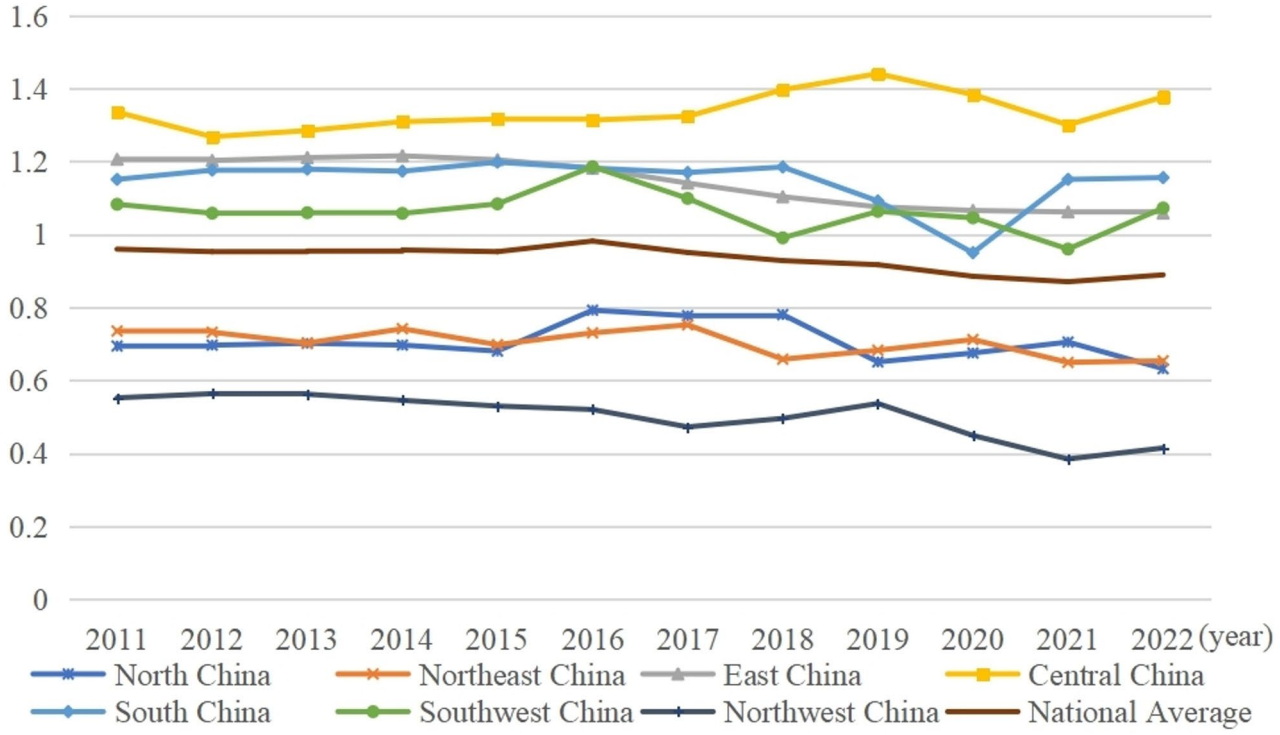

Fig. 2. Development level of AGG in different regions from 2011 to 2022.

In terms of provinces, 15 provinces had an AGG level above 1 in 2011, accounting for 48.39% of all provinces in China. Among them, Hunan had the highest level of AGG (1.552), while the Tibet Autonomous Region had the lowest agglomeration level (0.101). By 2022, there remained 15 provinces with a higher AGG level than 1. The province with the highest agglomeration level remained Hunan (1.649), and the Tibet Autonomous Region continued to exhibit the lowest agglomeration level (0.076). This indicates that the changes in the level of AGG across regions have remained relatively stable.

Measurement of ISU

The mediating variable in this study is ISU, which represents the transition from a traditional industrial model—characterized by heavy reliance on labour and capital inputs—to an advanced development model centred on knowledge, technology, and digitalisation. Considering data availability and indicator effectiveness, this study followed the methodology of Cao et al.[62] and measured ISU using the ratio of the output value of agricultural, forestry, animal husbandry, and fishery services to the total output value of these sectors. A higher ratio signifies a greater proportion of agricultural service industries, indicating a more advanced agricultural industrial structure and a higher level of service sector development within agriculture.

Other control variables

To comprehensively analyse the positive role of the AGG in enhancing NQPP, this study also accounted for key variables that affect the estimation results. These variables included: ① urbanization rate (UR): measured as the proportion of the urban population in each region at the end of the year relative to the total population; ② level of agricultural economy development (AE): expressed as the ratio of the total value of agricultural, forestry, animal husbandry, and fishery production to the number of individuals employed in agriculture; ③ comparative advantage index (CA): expressed as the ratio of a region's share of national pork production to its share of the national value of animal husbandry production; ④ food resources (FR): measured as the proportion of a region's grain output relative to the total national grain output; ⑤ water resources (WR): calculated as the ratio of a region's total water resources to the total national water resources; ⑥ production layout (PL): represented by the ratio of a region's pig slaughter volume to the total national pig slaughter volume; ⑦ environmental regulation (ER): expressed by adjusting the coefficient to refine the actual GDP, reflecting the regional level of economic development. The calculation formula is as follows:

$$ER = GDP \times \frac{1}{2/3 \times \sqrt{area/\pi}}$$

where ER represents the strength of environmental regulation, GDP is the regional gross domestic product, the area represents the regional area of each province, and π is the circular constant.

Data sources and descriptive statistics

Considering the availability and consistency of data over time, this study employed panel data from 31 provinces in China spanning the years 2011 to 2022 as its research sample. The data primarily originate from the "China Rural Statistical Yearbook", "China Statistical Yearbook", "China Statistical Yearbook on Environment", "Yearbook of Labour Statistics of China", "Institute of Digital Finance, Peking University", "China Energy Statistical Yearbook", "National Agricultural Product Cost-Benefit Data Compilation", and the "EPS DATA". Interpolation methods were applied to address any missing data.

Table 2 presents the descriptive statistics of the main variables, while Table 3 provides the correlation analysis between variables. The dataset exhibits no outliers or severe multicollinearity issues and remains relatively stable overall.

Empirical test

Analysis of baseline regression results

Table 4 presents the regression results for the mixed OLS regression, province-fixed effects, year-fixed effects, and two-way fixed effects. Specifically, Column (1) reports the mixed OLS regression results examining the impact of AGG on the enhancement of NQPP. The regression coefficient of AGG is significantly positive at the 1% level, indicating that AGG plays a significant role in promoting NQPP enhancement. Columns (2) and (3) display the regression results while controlling for province-fixed and year-fixed effects, respectively. The regression coefficients of AGG remain significantly positive at the 1% level. Column (4) presents the regression results of the two-way fixed effects model. The regression coefficient of AGG remains significantly positive and passes the significance test at the 1% level, indicating that AGG can significantly promote NQPP enhancement, regardless of the chosen benchmark regression model. These findings confirmed H1. Furthermore, the Hausman

Variable type	Variable	Obs.	Mean	Std.	Min.	Max.
Explanatory variable	NQPP	372	1.200	0.534	0.023	3.173
Core explanatory variable	AGG	372	0.933	0.399	0.043	1.749
Mediating variable	ISU	372	4.254	2.030	-0.414	13.144
Control variables	UR	372	59.170	12.985	22.710	89.600
	AE	372	6.116	3.212	1.027	18.484
	CA	372	0.932	0.407	0.057	1.946
	FR	372	3.225	2.869	0.043	11.575
	WR	372	3.226	3.332	0.028	18.931
	PL	372	3.230	2.713	0.023	10.653
	ER	372	43.402	45.035	0.467	244.667

Table 2. Descriptive statistics.

Variable	NQPP	AGG	ISU	UR	AE	CA	FR	WR	PL	ER
NQPP	1									
AGG	0.174***	1								
ISU	−0.024	0.156***	1							
UR	−0.374***	0.073	-0.067	1						
AE	−0.128**	0.020	0.048	0.692***	1					
CA	0.029	0.881***	0.187***	0.139***	0.003	1				
FR	0.468***	0.053	0.142***	−0.173***	−0.029	−0.015	1			
WR	0.529***	0.089*	-0.250***	−0.514***	−0.245***	0.013	−0.066	1		
PL	0.685***	0.519***	0.186***	−0.239***	−0.151***	0.462***	0.614***	0.260***	1	
ER	−0.240***	0.266***	0.106**	0.693***	0.453***	0.274***	-0.095*	−0.263***	0.004	1

Table 3. Correlation analysis of variables. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)	(4)
Variable	NQPP	NQPP	NQPP	NQPP
AGG	0.288***	0.546***	0.527***	0.623***
	(3.394)	(6.491)	(8.225)	(10.336)
UR	0.005**	0.021***	0.004**	0.014***
	(2.039)	(6.991)	(2.326)	(3.423)
AE	0.011	0.032***	−0.055***	0.006
	(1.645)	(5.054)	(−7.488)	(1.173)
CA	−0.590***	−0.445***	−0.737***	−0.539***
	(−7.093)	(−6.176)	(−10.588)	(−9.599)
FR	0.010	0.043	0.023***	0.025
	(1.214)	(0.825)	(4.472)	(0.715)
WR	0.059***	−0.017	0.052***	−0.019**
	(9.788)	(−1.228)	(12.789)	(−2.245)
PL	0.136***	0.120***	0.109***	0.082***
	(13.298)	(3.286)	(15.869)	(4.197)
ER	−0.002***	0.002	−0.0004	−0.004**
	(−4.543)	(1.084)	(−1.382)	(−2.034)
Constant	0.556***	−1.938***	0.468***	−0.445
	(4.239)	(−5.110)	(4.543)	(−0.837)
Province fixed	NO	YES	NO	YES
Year fixed	NO	NO	YES	YES
Observations	372	372	372	372
R^2	0.710	0.938	0.849	0.975
Hausman test	88.05[0.000]			

Table 4. Results of the baseline regression. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; () represent t values.

test results indicated that the fixed effects model was superior to the random effects model. Comparing the goodness-of-fit coefficients of the fixed effects models revealed that the two-way fixed effects model exhibited the best fit. Therefore, this study used a measurement method that controls for the double fixed effects of province and year to construct the basic evaluation framework for assessing the impact of AGG on the enhancement of NQPP, serving as our benchmark regression model. Consequently, the results in Column (4) served as the core reference, offering the most accurate quantitative representation of the relationship between AGG and NQPP. The findings suggest that, after controlling for other factors, a 10% increase in AGG led to a 6.23% enhancement in NQPP. The results for the control variables indicated that UR, and PL exhibit a significant positive correlation with improvements in NQPP, passing the significance test at the 1% level. This indicates that higher levels of UR correspond to greater market demand for pork products, thereby facilitating the structural adjustment of supply within the pig farming industry. Optimizing PL could facilitate the realization of scale economies, accelerates technological diffusion, and enhances specialized division of labour. These synergistic effects collectively reduce production costs while improving operational efficiency, ultimately driving the development of NQPP. While AE and FR demonstrate potential to enhance NQPP, their impacts remain statistically marginal. This finding

reflects a critical transition period in China's pig industry - shifting from "resource dependent" growth to "innovation driven" development, which urgently requires improved resource conversion efficiency through both husbandry paradigm transformation and technological innovation. Conversely, the CA, WR, and ER exhibit significant negative impacts on the enhancement of NQPP. This phenomenon may be explained through several mechanisms. On one hand, resource constraints and cost pressures have reduced the competitiveness of the pork market. These financial pressures have created significant barriers to investment in two critical areas: advanced breeding technologies and modern management practices. The resulting technological stagnation directly inhibits productivity growth and innovation capacity across the pig industry. On the other hand, the increasingly stringent environmental regulations, while well-intentioned to promote sustainable development, have inadvertently created structural barriers. The mandatory low-carbon transition has proven particularly challenging for small and medium-scale farms, which often lack the financial resources and technical capabilities to comply with new environmental standards. This has led to the premature exit of numerous marginal producers from the market, ultimately reducing the overall momentum for NQPP enhancement across the industry.

Endogeneity treatment and robustness tests

Endogeneity treatment

To address potential endogeneity issues arising from reverse causality in the baseline regression, this study employed the IV method and the two-step system GMM estimation approach (Table 5).

The first method utilized is the IV approach. Given the potential reverse causality between AGG and NQPP, as well as the influence of unobservable variables, endogeneity concerns may lead to biased estimation results. To mitigate these issues, this study followed the methodology of Du et al.[63], employing the IV method to control for the aforementioned endogeneity. Regarding the selection of IV, This study utilizes average terrain slope as the IV for AGG, based on the following considerations. On one hand, the average terrain slope serves as a critical factor influencing both transportation infrastructure development and labour intensity. Generally speaking, steeper slopes correlate with greater construction difficulties and higher costs for transportation infrastructure, which consequently affects logistics conditions essential for the pig industry. Simultaneously, pronounced topographic gradients tend to inhibit labour concentration and mobility, leading to reduced labour density. Under such geographical constraints, AGG incentives diminish accordingly, while simultaneously creating barriers to the influx of new production factors into the region. Therefore, the average terrain slope demonstrates a strong association with AGG, satisfying the relevance requirement between the IV and the endogenous explanatory variable (AGG). On the other hand, terrain slope constitutes a naturally formed, geographically objective factor that does not directly influence the formation of NQPP, thereby exhibiting exogenous characteristics. To account for potential temporal heterogeneity in the slope-agglomeration relationship and to mitigate limitations inherent to cross-sectional IV, we employ an interaction term between province-level mean terrain slope and annual dummy variables as the IV for AGG. This approach effectively captures time-varying instrumental effects while maintaining exogeneity. The analysis subsequently adopts 2SLS regression to estimate. The IV test results, presented in Column (1) of Table 5, indicated that even after addressing endogeneity, AGG continues to significantly promote the enhancement of NQPP. For the weak identification test of the IV, the Kleibergen–Paap rk LM statistic produces a p-value of 0.000, strongly rejecting the null hypothesis of IV under-identification. Additionally, in the weak instrument identification test, the Kleibergen–Paap rk Wald F statistic exceeds the

	(1)		(2)
Variable	**AGG**	**NQPP**	**NQPP**
L.NQPP			0.574***
			(2.911)
AGG		0.965***	0.539**
		(3.923)	(2.161)
IV	−0.002***		
	(−4.683)		
Control variable	YES	YES	YES
Province fixed	YES	YES	YES
Year fixed	YES	YES	YES
Kleibergen-Paap rk LM statistic	21.357[0.0000]		
Kleibergen-Paap Wald rk F statistic	21.932{16.38}		
AR (1)			0.031
AR (2)			0.136
Hansen test			0.998
Observations	372	372	341
R^2	0.310	0.825	

Table 5. Endogeneity tests. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; (),[] and{} represent t values, P values, and critical values at 10% level of the stock logo weak recognition test, respectively.

critical threshold at the 10% significance level in the Stock–Yogo weak instrument test, confirming the validity of the chosen instrumental variable.

The second method employed the two-step system GMM estimation. The enhancement of NQPP is a dynamic and continuous process, meaning that its current level may be influenced by past values. To capture this dynamic characteristic, this study included the one-period lag of NQPP in the model to construct a dynamic panel dataset and then applied the two-step system GMM method for regression analysis. The model is constructed as follows:

$$NQPP_{i,t} = \alpha_0 + \alpha_1 NQPP_{i,t-1} + \alpha_2 AGG_{i,t} + \alpha_3 Z_{i,t} + \mu_i + \sigma_t + \varepsilon_{i,t} \quad (4)$$

where $NQPP_{i,t-1}$ denotes the one-period-lagged new quality productive forces in the pig farming industry. The coefficients are identical to those in Eq. (1).

Compared to difference GMM, system GMM not only imposes stricter model assumptions that effectively address endogeneity issues, but also delivers more accurate estimation results. Therefore, this study employs the two-step system GMM method, with the test results presented in column (2) of Table 5. The findings indicate that the second-order serial correlation test was satisfied [AR(1) < 0.1, AR(2) > 0.1], and the IV are valid (Hansen test $p > 0.1$). The coefficient of AGG is 0.539, which remains significant at the 1% level, demonstrating that AGG continues to significantly promote the enhancement of NQPP. Therefore, the research conclusions remain robust.

Robustness tests

In this study, three methods were employed to conduct robustness tests, ensuring the robustness and reliability of the main conclusions (Table 6).

Analysis of mediating effects

The first method involved replacing the core explanatory variable. Specifically, the ratio of pig farming output to total agricultural, forestry, animal husbandry, and fishery output was used as an alternative measure of AGG as the explanatory variable for robustness testing. The results (Column 1) show that AGG's positive effect on NQPP remains significant at the 1% level. The second method involved replacing explained variable. To avoid estimation bias caused by measurement methods, this study employs the entropy weight method to recalculate NQPP. The estimates (Column 2) are consistent with baseline results in both magnitude and significance. The third method involved excluding the influence of partial factors. During the research period, two major events may have significantly impacted the hog farming industry: the African swine fever outbreak in 2018 and the COVID-19 pandemic in 2019. Given the difficulty in controlling for such events with specific variables, we exclude the data from these years to ensure the robustness of our results. Furthermore, due to the lasting effects of these events, we also omit data from subsequent years. As a result, the regression analysis is restricted to the period 2011–2017. The regression results from this restricted sample are presented in column (3) of Table 6. The direction and significance of the regression coefficient for AGG remain unchanged.

In summary, all robustness checks yield results consistent with the conclusions of this study. The coefficient estimates and their significance did not exhibit significant changes, further demonstrating the robustness and reliability of the findings.

The previous section provided a theoretical analysis of the mechanism by which AGG influences the enhancement of NQPP from the perspective of ISU. This study employed a mediation effect model to examine this impact and verify the hypothesis. The regression results are presented in Table 7. As shown in Column (1), AGG exhibits a statistically significant positive effect on NQPP. Column (2) evaluates the impact of AGG on ISU, revealing a significantly positive regression coefficient for AGG, which confirms its robust promotional effect on ISU. According to industrial structure theory, ISU drives the reallocation of production factors from low-value-added sectors to high-value-added sectors through a triple-helix interaction of industrial convergence, technological penetration, and institutional innovation. In the pig industry, the economies of scale, knowledge spillover, and innovation effects generated by AGG not only facilitate the integration of the pig industry chain and the optimal allocation of production factors but also create regional advantages for industrial structure adjustment. Existing research demonstrates that ISU optimizes resource allocation and facilitates production

Variable	NQPP		
	(1)	(2)	(3)
AGG	0.038***	0.076***	0.738***
	(14.375)	(4.251)	(6.443)
Constant	−0.113	−0.176	1.097
	(-0.264)	(−1.408)	(1.413)
Control variable	YES	YES	YES
Province fixed	YES	YES	YES
Year fixed	YES	YES	YES
Observations	372	372	217
R^2	0.985	0.941	0.985

Table 6. Robustness tests. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; () represent t values.

Variable	(1)	(2)
AGG	0.623***	1.889***
	(10.336)	(3.311)
Constant	−0.445	−9.076**
	(−0.837)	(−2.541)
Control variable	YES	YES
Province fixed	YES	YES
Year fixed	YES	YES
Observations	372	372
R^2	0.975	0.873

Table 7. Results of the mediation effect test. *, **, and *** are significant at the 10%, 5%, and 1% levels, respectively; ( ) are t values.

Threshold variable	Model	F-stat	*P*-value	10% critical	5% critical	1% critical
ISU	Single threshold	22.37	0.07	20.622	23.789	28.646
	Double threshold	5.63	0.81	18.517	21.238	30.181
	Threshold type	Threshold value	95% lower		95% upper	
	Single threshold	1.820	1.818		1.859	

Table 8. Results of the threshold effect test.

Variable	Threshold Variable: ISU
	NQPP
AGG×I (ISU ≤ 1.820)	0.634***
	(5.371)
AGG×I (ISU > 1.820)	0.707***
	(6.882)
Constant	−0.078
	(−0.260)
Control variable	YES
Province fixed	YES
Year fixed	YES
Observations	372
R^2	0.611

Table 9. Threshold effect regression result. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; () represent t values.

factor advancement.This resource reallocation process and factor restructuring effectively fosters the development of new-quality labour, new-quality objects of labour, and new-quality means of production within the pig industry, thereby enhancing NQPP. Therefore, ISU plays a critical mediating role in the relationship between AGG and NQPP enhancement. H2 is supported.

Analysis of non-linear effects

Building on the preceding theoretical analysis, the promotive effect of AGG on NQPP is partially mediated by ISU, suggesting the potential existence of a threshold effect based on ISU. Before performing the threshold model regression, testing whether a panel threshold effect exists is necessary. Following a bootstrap method with 300 resampling iterations, the results are presented in Table 8. The ISU passes the single-threshold effect test and the estimated threshold values is 1.820.

Table 9 presents the threshold regression results analyzing the effect of AGG on NQPP enhancement. The analysis reveals significant nonlinear dynamics in AGG's promotional effect on NQPP, which vary systematically with the progression of ISU. When ISU ≤ 1.820, the regression coefficient of AGG is 0.634, statistically significant at the 1% level. For ISU > 1.820, the coefficient increases to 0.707, also significant at the 1% level. These results indicate that ISU amplifies the positive impact of AGG on NQPP enhancement, exhibiting an increasing marginal effect with non-linear characteristics. Therefore, H3 was validated.

Variable	NQPP						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
AGG	0.575***	0.695***	0.489***	0.560***	0.002	0.784***	1.181***
	(5.948)	(8.288)	(5.657)	(3.075)	(0.006)	(6.663)	(5.983)
Constant	−1.060	1.863	0.380	2.755	−5.413**	−2.089	0.008
	(-0.879)	(0.766)	(0.256)	(1.199)	(−2.440)	(−1.415)	(0.006)
Control variable	YES	YES	YES	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES	YES
Observations	60	36	84	36	36	60	60
R^2	0.996	0.989	0.989	0.978	0.996	0.977	0.981

Table 10. Results of the analysis of geographical heterogeneity. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; () represent t values.

Variable	NQPP		
	High	Medium	Low
AGG	0.490***	0.484***	0.829***
	(3.516)	(8.193)	(4.335)
Constant	−2.491**	0.785*	−0.177
	(−2.169)	(1.810)	(−0.082)
Control variable	YES	YES	YES
Province fixed	YES	YES	YES
Year fixed	YES	YES	YES
Observations	72	252	48
R^2	0.981	0.977	0.986

Table 11. Heterogeneity analysis of comprehensive technological innovation level. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively; () represent t values.

Heterogeneity analysis

Analysis of geographical regional heterogeneity

Considering the variations in economic development across different regions owing to geographic location and other factors, this study categorizes China's 31 provinces into seven regions—North China, Northeast China, East China, Central China, South China, Southwest China, and Northwest China—based on China's geographic divisions to conduct a sub-sample regression analysis (Table 10), Columns (1)–(7) present the NQPP in these respective regions. The results indicate that, with the exception of South China, AGG promotes the enhancement of NQPP in all other regions. In South China, although AGG contributes to the enhancement of NQPP, its effect is not significant. A possible explanation for this is that South China is predominantly characterized by non-agricultural industries (manufacturing and service industry), where resources are allocated toward high-value-added sectors. This allocation results in relatively limited capital and technological investment in the pig industry within agglomeration areas. Thus, large-scale pig farming faces stringent land-use approvals and high environmental compliance costs. Consequently, enterprises in this region tend to prioritize emerging technology industries, making AGG beneficial for enhancing NQPP but with limited overall effectiveness.

Comprehensive technological innovation heterogeneity analysis

Given the varying levels of technological innovation across China's provinces—encompassing differences in the technological innovation environment, technological activity input, and technological activity output—the 31 provinces are categorized into high, medium, and low level innovation regions for subsample regression analysis based on the "China Regional Science and Technology Innovation Evaluation Report 2023". The impact of AGG on the enhancement of NQPP was then compared across these different levels of technological innovation for each sample (Table 11). It can be observed that the regression coefficients of AGG are significantly positive at the 1% level across all innovation regions. This further demonstrates that the allocation and flow of innovation factor resources can promote the digital transformation of the pig farming industry, technological innovation is a key driver in fostering the enhancement of NQPP.

Discussion

Improving the development of NQPP is crucial for promoting the high-quality advancement of the sector and achieving the "dual-carbon" goals. As a spatial organizational form of industries, AGG serves as an effective

mechanism for concentrating and optimizing resource allocation. Compared with existing studies, this study makes several significant contributions.

In analysing the baseline regression results, this study empirically examined the impact mechanism and confirmed that AGG significantly enhances the development of NQPP. This conclusion remains robust across a series of stability tests. Notably, this finding aligns with the conclusions of Dong et al.[64] and Liu et al.[65], who demonstrated that AGG significantly improves total factor productivity in the livestock sector through economies of scale, knowledge spillovers, and technological diffusion effects. Although limited research exists on the relationship between AGG and NQPP, this study further validated the critical role of AGG in fostering NQPP development. The key contribution of this study lies in introducing the relationship between AGG and NQPP within the context of the pig industry and empirically verifying its significant positive impact.

Regarding transmission pathways and mechanism analysis, ISU plays a key role in the relationship between AGG and the enhancement of NQPP, serving as an intrinsic driver of their improvement. Specifically, AGG facilitates the vertical integration and horizontal expansion of the pig industry, fostering a more efficient system of labour division and cooperation. Simultaneously, ISU enables the reallocation of resources from low-efficiency to high-efficiency sectors, thereby optimizing resource allocation efficiency. As ISU progresses, the pig industry is transitioning from a labour-intensive to a technology-intensive sector, thereby significantly contributing to the development of NQPP. This finding aligns with the research of Yao et al.[66] and Xie et al.[43], further validating the critical role of ISU in improving NQPP. The innovation of this study lies in its introduction of ISU as a mediating variable within the unified framework of AGG and NQPP enhancement, offering a novel perspective on the underlying mechanisms linking them. Furthermore, this study reveals that the spillover effect of AGG on NQPP exhibits a significant non-linear characteristic of increasing marginal effects. This observation is consistent with the study's initial hypothesis. Specifically, in the early stages of AGG, its promotional effect may primarily stem from economies of scale and resource sharing. However, as the degree of agglomeration intensifies, the effects of technological advancements and structural transformation become more pronounced, further amplifying AGG's positive influence on NQPP enhancement. This finding has important policy implications. During the agglomeration process of the pig farming industry, policymakers should prioritize enhancing the quality of pig farming enterprises and fostering an innovation-friendly environment. Such efforts will better promote technological innovation and the transformation of scientific and technological achievements. Additionally, this study's findings align with existing literature[26,67] on the non-linear effects of AGG.

In the heterogeneity analysis, this study examines the impact of AGG on the enhancement of NQPP from two perspectives: regional heterogeneity and technological innovation heterogeneity, further elucidating the complexity of this relationship. Regarding regional heterogeneity, the findings indicate that AGG promotes the enhancement of NQPP across all regions except South China. Notably, East China, Central China, and Southwest China not only possess superior natural resource endowments but also feature favourable productivity factors and functional advantages, enabling them to better leverage the agglomeration effect. This finding aligns with the studies of Zhang et al.[68]. However, an intriguing phenomenon emerges in Northeast China: despite lower-than-average levels of AGG, AGG still significantly enhances NQPP. This seemingly paradoxical finding can be attributed to supportive policies and structural alignment with market demand, which transform economies of scale derived from agglomeration into economies of quality[69]. For example, Northeast China has implemented the "Agricultural Revitalization Plan", which channels subsidies, land, and financial resources into agglomeration areas, creating policy-driven advantages that stimulate industrial growth. In contrast, the exceptional case of South China may be linked to factor congestion, resource constraints, or the policy environment. Future research should further investigate the underlying causes of this regional divergence. Regarding technological innovation heterogeneity, the findings suggest that, regardless of the level of technological innovation, AGG consistently promotes the enhancement of NQPP. This finding reinforces the notion that technological innovation serves as a core driver of NQPP enhancement. Based on these findings, policymakers should carefully consider regional differences in AGG levels and factor endowments across regions and adopt region-specific, differentiated policy measures to maximize the benefits of AGG in enhancing NQPP.

Conclusions and recommendations

This study empirically examined the transmission mechanism and impact of AGG on the enhancement of NQPP using panel data from 31 provinces in China from 2011 to 2022. The key findings are as follows: First, AGG significantly promotes the improvement of NQPP, a conclusion that remains valid across various robustness tests. Second, AGG indirectly enhances NQPP by promoting ISU, indicating that ISU serves as an internal driving force for NQPP enhancement. Third, the spillover effect of AGG on NQPP improvement exhibits a significant non-linear characteristic, with an increasing marginal effect. The adjustment of industrial structures and the continuous improvement of technological innovation accelerate the transformation of scientific and technological achievements, thereby strengthening the positive impact of AGG on NQPP enhancement. Fourth, the promoting effect of AGG on NQPP enhancement varies regionally. Its impact is particularly pronounced in resource-rich regions with development potential.

Based on the aforementioned conclusions, this study proposes the following policy recommendations:

(1) Promote AGG to overcome the "low-end lock-in" dilemma. Empirical findings indicate that AGG significantly enhances NQPP. Therefore, further advancing the agglomeration of pig farming is crucial to fully leverage the scale effect, knowledge spillover effect, and innovation effect of AGG. Support should be provided for smart farming management models, such as intelligent feeding systems and environmental monitoring systems, to facilitate the development of high-quality labour, advanced production inputs, and improved means of production. These efforts will ultimately drive the enhancement of NQPP.

(2) Optimize industrial layout and implement targeted policies. The government should develop region-specific policies based on local resource endowments and the existing level of NQPP development. In regions with high NQPP development levels (e.g., Central China, and Southwest China), efforts should focus on capitalizing on AGG's advantages by promoting large-scale and intensive development. Conversely, in regions with lower NQPP development levels (e.g., North China and Northwest China), policies should be tailored to local conditions, identifying growth potential and exploring differentiated development pathways to enhance industrial competitiveness.
(3) Strengthen regional coordination to enhance the spillover effects of AGG. As technological innovation increasingly drives industrial transformation and upgrading, establishing regional collaboration mechanisms is crucial. In regions with high AGG development levels (e.g., Central China, South China, East China, and Southwest China), the mobility of capital, technology, and labour should be fully utilized to foster cross-regional cooperation in the pig farming industry, including information and technology sharing. These initiatives will stimulate intrinsic momentum for enhancing NQPP. Meanwhile, in regions with lower AGG development levels (e.g., Northeast China, Northwest China, and North China), efforts should focus on maximizing AGG's benefits while strengthening interregional exchanges and cooperation. Additionally, the establishment of interest-linkage mechanisms should be encouraged to comprehensively advance NQPP.

Data availability

All data generated or analysed during this paper are included in this published article.

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Y. X. wrote the original draft. Y. Y. was responsible for the conception, design, review, and editing. Y. X. contributed to the data collection and processing.All authors reviewed the manuscript.

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Declarations

Competing interests
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