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# Driving Mechanisms and Heterogeneous Moderating Effects of Green Technology Innovation in Agricultural Enterprises Under the TOE Framework

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**Abstract:** According to the "dual carbon" strategy, the greening transformation of enterprises in agriculture is essential. Yet, there is inadequate literature on the mechanisms that drive green technological innovation, particularly in accounting for differences among firms. This study is based on the technology, organization, and environment framework. It constructs a model of the driving mechanisms using green technology innovation in agricultural enterprises. Firm size, ownership type, and regional differences are introduced as moderating variables. To systematically explore the effects of various driving factors and their heterogeneous moderating effects. This study conducts a multiple regression analysis of survey data from Chinese agricultural enterprises. The results show that technological, organizational, and environmental factors all positively drive green technology innovation, with technological factors contributing the most. Firm size is positively associated with Green Technological Innovation (GTI) and positively moderates the effect of technological factors on GTI. In contrast, the moderating effects of ownership type and regional differences are not significant. The moderating effects of ownership type and regional differences are not substantial, although state-owned enterprises and enterprises in eastern regions have higher average innovation levels. The impact of technological factors shows a continuously increasing marginal effect, while organizational factors display a decreasing marginal effect. The study reveals that green technology innovation in agricultural enterprises is a complex process driven by both internal and external factors, providing theoretical guidance and practical reference for differentiated industrial policies and for guiding agricultural enterprises toward sustainable green development.

**Keywords**: Green technology innovation, agricultural enterprises, TOE framework, driving mechanisms, enterprise heterogeneity.


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## 1. Introduction

### 1.1. Research Background

In the context of the "dual carbon" strategy, the agricultural industry is under extraordinary pressure to undergo green transformation. When compared to industries like manufacturing, agricultural production has greater external effects, wider ecological consequences, and a longer chain value, which means that green development is not only linked to business performance, but also to the security of the ecosystem and social well-being (Feng et al., 2022). Green Technological Innovation (GTI) represents a way to achieve economic and environmental performance in harmony. However, agricultural companies are generally smaller, have fewer capital assets and research and development capabilities than their manufacturing counterparts, which makes it difficult for them to adopt GTI due to high costs, a longer timeline, and greater risks (Li et al., 2023). It is necessary to comprehensively explore the drivers of GTI at the company level and elaborate on the factors causing heterogeneity and constraints that drive the mechanisms.

### 1.2. Research Significance

The study has significant theoretical and practical value. The Technology-Organization-Environment (TOE) framework, proposed by Tornatzky and Fleischer, emphasizes that technological, organizational, and environmental factors jointly determine innovation adoption behavior (Li et al., 2024; Low et al., 2022). Prior research has applied the TOE framework primarily in manufacturing contexts, such as digital transformation and IT adoption, with limited discussion of its suitability for GTI in agricultural enterprises. This study expands the use of the TOE framework in the area of agricultural GTI through the consideration of the factors of technology, organization, and environment, as well as an agricultural perspective that is consistent with the green development goal of simultaneously achieving economic and ecological outcomes. From a practical perspective, understanding the nature of the three dimensions and the diversity within each will enable the enterprise to make wise investments and assist the government in implementing differentiated policies.

### 1.3. Research Approach

From a TOE-based analytical perspective, this study constructs a technology–organization–environment driver framework to explain how technological, organizational, and environmental factors jointly affect green technology innovation in agricultural enterprises. In addition, firm size, ownership type, and regional differences are incorporated to examine heterogeneous moderating effects, while firm age, agricultural sub-industry, and leverage are included as control variables. In Fig. 1, Age refers to firm age, Sub-industry refers to the agricultural sub-sector in which the enterprise operates, and Leverage refers to capital structure, measured by the liability-to-asset ratio. Solid lines indicate the hypothesized direct effects of the TOE factors on green technology innovation, whereas dashed lines indicate moderating or control relationships included in the empirical model. The conceptual model of the driving mechanism is presented in Fig. 1.

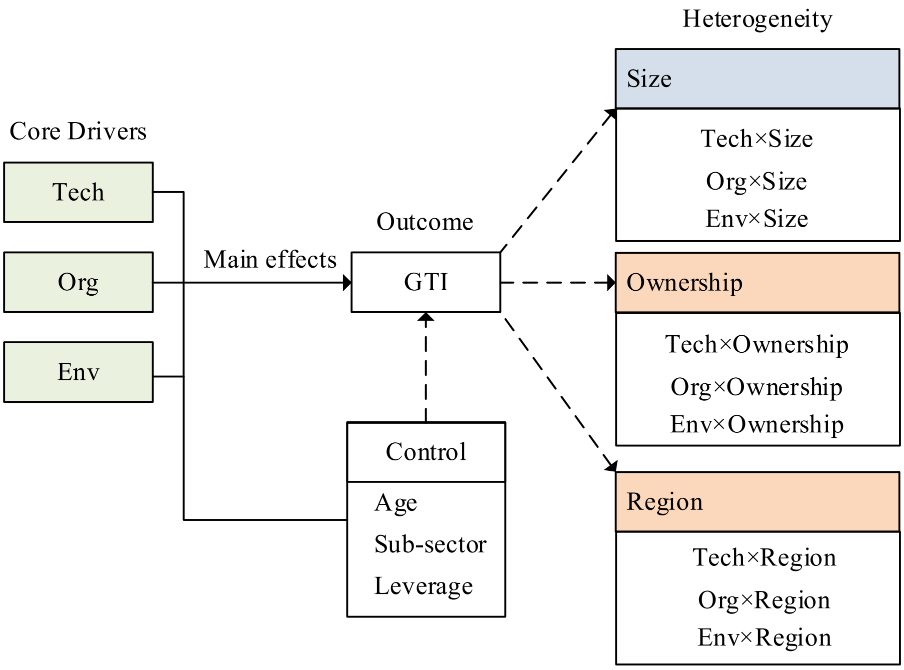


**Fig. 1.** The conceptual model of the driving mechanism

Note: Age = firm age; Sub-industry = agricultural sub-sector; Leverage = liability-to-asset ratio. Solid lines indicate direct effects, and dashed lines indicate moderating or controlling relationships.

### 1.4. Research Hypotheses

This study focuses on the moderating effects of enterprise heterogeneity and proposes the following hypotheses:

H1: Firm size positively moderates the effect of technological factors on green technology innovation.

H2: Ownership type moderates, with state-owned enterprises showing stronger responses to organizational and environmental factors than private enterprises.

H3: Regional differences moderate the effects of technological and environmental factors, with these factors having greater effects in enterprises located in eastern regions.

## 2. Literature Review

Green technology innovation refers to the application of technologies and practices in product design, production processes, and management models that focus on energy saving, emission reduction, resource recycling, and ecological protection, aiming to achieve both economic and environmental benefits. Xu et al. (2023) found that green technology innovation significantly promotes economic low-carbon transformation. In contrast, local government competition significantly inhibits the low-carbon transition process and weakens the positive effects of green technology innovation. In areas with low competition intensity, the promoting effect of green technology innovation is weaker, and the inhibitory effect of government competition is more substantial. However, existing studies primarily focus on economic benefits at the enterprise level, with limited consideration of ecological system characteristics in agriculture. Few studies comprehensively integrate technological, organizational, and external environmental factors, and enterprise heterogeneity is often overlooked.

The TOE framework introduced by Eveland and Tornatzky posits that technology adoption and innovation are affected by technological, organizational, and environmental aspects (Yan et al., 2024). Since its emergence, the TOE framework has become quite popular in the fields of IT adoption, digital governance, and green supply chains (Chembessi et al., 2022). Alraja et al. (2022) investigated how small and medium enterprises maintain sustainable performance during the pandemic and developed a holistic approach to integrating the TOE and resource-based perspectives into a sustainable performance framework. The combination of three TOE constructs serves as the primary input for green practices, including green training and performance evaluation, and acts as a mediator of sustainable performance achievement. However, research on agricultural enterprises remains limited, and existing studies still have room for improvement in indicator selection and analytical depth. Enterprise heterogeneity refers to differences in size, ownership, and regional environment among firms, leading to variations in innovation capacity, resource endowment, and business objectives. Existing studies emphasize the differentiated responses of enterprises to incentives for green technology innovation. Xue et al. (2022) found that Fintech has more substantial promotional effects in eastern regions, on invention patents, on state-owned enterprises, and on firms with low environmental uncertainty, highlighting the role of institutional support and regional differences in green innovation. Lai et al. (2022) examined whether environmental awards incentivize firms to engage in green technology innovation, finding that the effect is significant only for non-state-owned enterprises, high-financial-risk firms, and high-pollution enterprises. Zhao et al. (2022) reported that carbon emission trading policies significantly promote green technology innovation in resource-based industries, particularly among large and non-state-owned enterprises, indicating significant differences in policy incentives by enterprise size and ownership. Nevertheless, studies on heterogeneity often focus on a single dimension, lack comprehensive analysis, and rarely quantify interaction effects.

The TOE drivers of GTI in agricultural enterprises are subject to stronger context-specific constraints. Natural risks and seasonal volatility raise trial-and-error costs and increase uncertainty in payback periods, making “technology availability and convertibility” a key threshold for moving from adoption to sustained innovation. Meanwhile, institutional arrangements, such as regulatory standards, subsidy rules, and compliance inspections combined with supply-chain coordination (lead-firm leadership, cross-regional operations, and distribution networks) mean that organizational and environmental factors more often amplify the innovation returns to technological investment through “resource integration–coordinated implementation–compliance calibration.”

Earlier work has established that external environments (such as digital finance, environmental sanctions, and competition among governments) can foster GTI. Nevertheless, their samples tend to be dominated by industrial sectors or across all industries, while little attention is paid to agricultural aspects, such as restrictions due to natural risks, coordination within agrifood systems, and different mechanisms of adherence to requirements. The TOE approach will be utilized here to “mechanize” macro-institutional factors in terms of the agricultural business sector. Moreover, since green innovation research is becoming more focused on “configurations/pathways,” rather than “net effects,” the current study adds to this trend.

## 3. Research Design and Data Sources

### 3.1. Research Questions and Variable Design

This study focuses on Chinese agricultural enterprises. Firm-level information was primarily collected through a structured questionnaire survey, and key items were cross-validated using publicly disclosed materials (e.g., annual reports, CSR reports, and policy documents). The survey covered firm characteristics, R&D investment, organizational structure, technology adoption, and perceptions of market and policy environments. After data cleaning, 500 valid observations were retained. To enhance national coverage, stratified quota sampling was implemented by region (eastern vs. central-western China) and sub-sector (crop cultivation, livestock breeding, and agricultural product processing). The final sample comprises 270 firms from eastern China (54.0%) and 230 from central-western China (46.0%); it also includes 265 state-owned enterprises (53.0%) and 235 private enterprises (47.0%). To measure the degree of innovation in green technology, the number of patents applied for by firms is used as the main variable. The number of patents is log-transformed to minimize skew. Furthermore, annual reports of listed firms, firm CSR reports, and data obtained from local government sources are gathered to provide supplementary environmental factor variables. A summary of definitions and measures of the variables is provided in Table 1.

In Table 1, the dependent variable GTI is expressed as the logarithm of the number of green patent applications. Technological, organizational, and environmental factors are measured using indicators such as R&D investment, governance structure, and the external policy environment. Moderating variables include firm size, ownership type, and regional differences. Control variables cover firm age, industry type, and capital structure. For transparency, several anonymized example records from the collected dataset are reported in the Appendix table.

### 3.2. Research Methods

To empirically test the hypotheses, descriptive statistics and correlation analysis are first conducted to understand the sample's characteristics and the preliminary relationships among variables. Next, multiple linear regression models are constructed to analyze the effects of technological, organizational, and environmental factors on green technology innovation. Based on this, interaction terms with moderating variables are introduced to test heterogeneous moderating effects. Group regressions and robustness tests are conducted to ensure the reliability of the results. A baseline regression model is first constructed to quantify the effects of TOE’s three-dimensional factors on the level of green technology innovation in enterprises (Mouakket et al., 2023; Mouakket et al., 2022). The model uses the logarithm of green patent applications as the dependent variable, TOE three-dimensional indicators as core independent variables, and controls for firm age, industry type, and capital structure. The model aims to examine the fundamental drivers of technological accumulation, organizational capacity, and the external institutional environment on green innovation. The baseline regression model is expressed in Eq. (1).

**Table 1.** Variable definitions and measurement methods

| Variable | Definition | Measurement method |
|---|---|---|
| GTI | Green Technology Innovation Level | ln(1 + Green patent applications); green patent counts cross-validated with publicly disclosed materials (annual reports/CSR/policy documents) where available. |
| Tech | Technological Factor | Multi-item construct (e.g., R&D input intensity, green technology/equipment adoption, digital-agriculture infrastructure). Items measured on a 5-point Likert scale; construct score built as an equal-weighted composite, then z-standardized. |
| Org | Organizational Factor | Multi-item construct (e.g., green innovation governance routines, human-capital support, internal coordination, incentives/training, environmental management routines). 5-point Likert; equal-weighted composite, then z-standardized. |
| Env | Environmental Factor | Multi-item construct (e.g., regulatory/compliance pressure, policy support/subsidy intensity, market demand for green products, supply-chain greening requirements). 5-point Likert; equal-weighted composite, then z-standardized. |
| Size | Enterprise Size | Ordinal size category based on employee scale: 1=small, 2=medium, 3=large (derived from the employee-count item); used as moderator/control. |
| Ownership | Ownership Type | Dummy Variable (State-owned=0, Private=1) |
| Region | Regional Difference | Dummy Variable (East=1, Central & West=0) |

$$GTI_i = \alpha + \beta_1 Tech_i + \beta_2 Org_i + \beta_3 Env_i + \gamma Control_i + \varepsilon_i \tag{1}$$

In Eq. (1), $GTI_i$ represents the green technology innovation level of the $i$-th enterprise. $Tech_i$, $Org_i$, and $Env_i$ denote technological, organizational, and environmental factors, respectively. $Control_i$ is the vector of control variables, and $\varepsilon_i$ is the random error term. $\alpha$ is the constant, and $\beta_1$, $\beta_2$, $\beta_3$ are coefficients of the explanatory variables, reflecting the strength of each factor's impact on green technology innovation. The application of the TOE framework in relation to heterogeneity and different mechanisms is analyzed through three different moderating variables, including firm size, ownership type, and regional differences. An interaction term regression analysis framework is used to verify the extent to which the moderating variables impact the effects of TOE drivers on environmental innovations. The heterogeneous moderating variable model is shown in Eq. (2).

$$GTI_i = \alpha + \beta_1 Tech_i + \beta_2 Org_i + \beta_3 Env_i + \delta_1 Tech_i \times M_i + \delta_2 Org_i \times M_i + \delta_3 Env_i \times M_i + \gamma Control_i + \varepsilon_i \tag{2}$$

In Eq. (2), $M_i$ represents the moderating variable, corresponding to firm size, ownership type, or regional differences. $Tech_i \times M_i$ denotes the interaction terms used to test the moderating effect, while $\delta_1$ to $\delta_3$ are coefficients of the moderating terms. Samples are stratified according to moderating variables, and regression analyses are repeated within each subgroup. Differences in regression coefficients reveal the heterogeneous effects of TOE dimensions across enterprise types. The group regression model is expressed in Eq. (3).

$$GTI_{i,g} = \alpha_g + \beta_{1g} Tech_i + \beta_{2g} Org_i + \beta_{3g} Env_i + \gamma_g Control_i + \varepsilon_{i,g} \tag{3}$$

In Eq. (3), $g$ indexes different enterprise groups. $\alpha_g$ represents the intercept for each group, $\beta_{1g}$, $\beta_{2g}$, $\beta_{3g}$ are slopes for each group, and $\varepsilon_{i,g}$ is the random error term. Considering that green innovation behavior has both continuous and categorical characteristics, a logistic regression model is introduced. Enterprises are classified into "high innovation level groups" as a binary dependent variable to test the probability effects of TOE factors on entering high innovation groups. Its expression is shown in Eq. (4).

$$\Pr(HighInnov_i = 1) = \frac{1}{1 + \exp(-(\alpha + \beta_1 Tech_i + \beta_2 Org_i + \beta_3 Env_i + \beta_4 Size_i + \beta_5 Ownership_i + \beta_6 Region_i))} \tag{4}$$

In Eq. (4), $HighInnov_i$ is a dummy variable, taking 1 if the $i$-th enterprise's green technology innovation level is above the sample median, and 0 otherwise. $\frac{1}{1+\exp(\cdot)}$ is the Logistic function, indicating the probability that an enterprise belongs to the high green innovation group. To ensure robustness, standard errors are whitened, and heteroscedasticity tests are conducted. In addition, the dependent variable is replaced with alternative indicators, such as the proportion of green revenue, to perform sensitivity analysis, ensuring that conclusions are not dependent on a single measurement. In addition, quantile regression is employed to examine distributional heterogeneity in the TOE effects. For any quantile $\tau$, the conditional quantile function of GTI is specified in Eq. (5).

$$Q_\tau(\mathrm{GTI}_i \mid X_i) = X_i^{\cdot} \beta(\tau), \ \ 0 < \tau < 1 \tag{5}$$

In Eq. (5), for a continuous driver, its marginal effect at quantile $\tau$ equals the corresponding slope coefficient $\beta(\tau)$. Because Tech, Org, and Env are z-score standardized indices, the coefficients can be interpreted as the change in GTI associated with a one-standard-deviation increase in the explanatory variable. Standard errors and statistical significance are evaluated using 1,000 bootstrap replications (two-sided tests). A marginal effect is considered statistically significant if the 95% bootstrap confidence interval does not include zero.

## 4. Empirical Results and Analysis

### 4.1. Descriptive Statistics and Correlation Test

The study first conducted descriptive statistics for the main variables. The results are shown in Table 2.

**Table 2.** Descriptive statistics of main variables

| Variable | Mean | Standard error | Minimum | Maximum |
|---|---|---|---|---|
| GTI | 0.190 | 1.112 | -4.338 | 2.804 |
| Tech | -0.006 | 0.984 | -3.241 | 3.853 |
| Org | -0.021 | 0.962 | -2.472 | 3.079 |
| Env | 0.080 | 0.997 | -2.697 | 2.632 |
| Size | 2.020 | 0.793 | 1 | 3 |
| Ownership | 0.470 | 0.500 | 0 | 1 |
| Region | 0.540 | 0.499 | 0 | 1 |

In Table 2, the mean of GTI for sample enterprises was 0.190, with a standard deviation of 1.112, a minimum of -4.338, and a maximum of 2.804, indicating differences among enterprises. On average, Tech had a value of -0.006 and a standard deviation of 0.984, suggesting differences in technology-related investments. On average, Org had a value of -0.021, which implied stability. Env, on the other hand, had an average of 0.082 and a standard deviation of 0.997, indicating large differences in perceptions of operating environments across enterprises. The average enterprise size was 2.02, suggesting a greater proportion of medium- to large-sized enterprises in the study sample. The average Ownership and Region values were 0.470 and 0.540, respectively.

### 4.2. Empirical Results of Driving Mechanisms

The baseline regression model was then tested, and the results are shown in Table 3.

**Table 3.** Baseline regression results

| Variable | Coefficient | Significance |
|---|---|---|
| Intercept | -0.207 | 0.241 |
| Tech | 0.441 | 0.000*** |
| Org | 0.231 | 0.000*** |
| Env | 0.246 | 0.000*** |
| Size | 0.189 | 0.008** |
| Ownership | -0.174 | 0.121 |
| Region | 0.156 | 0.168 |

As shown in Table 3, the coefficient for Tech was 0.441, significant at the 1% level and positive, indicating that technological investments and the development of information infrastructure increased the probability of adopting green technology innovation. The value of Org was 0.231, implying that the presence of abundant resources and coordination ability within firms allowed green innovations to take place. The value of Env was 0.246, which was positive, indicating that pressures from policy-making, market forces, and supply chains contributed to green innovations by enterprises. Among control variables, Size had a coefficient of 0.189, further confirming that larger enterprises had stronger green innovation capacity. Ownership had a coefficient of -0.174, indicating no significant difference in green innovation tendency between state-owned and private enterprises. The Region had a coefficient of 0.156, which was not significant, due to limited regional variation in the sample.

To further examine the effect of firm size on the TOE-based process, this study uses the interaction-term approach while considering firm size as a continuous variable. Marginal effects are estimated for each technological, organizational, and environmental factor at different levels of firm size on GTI. These results are shown graphically in Fig. 2.

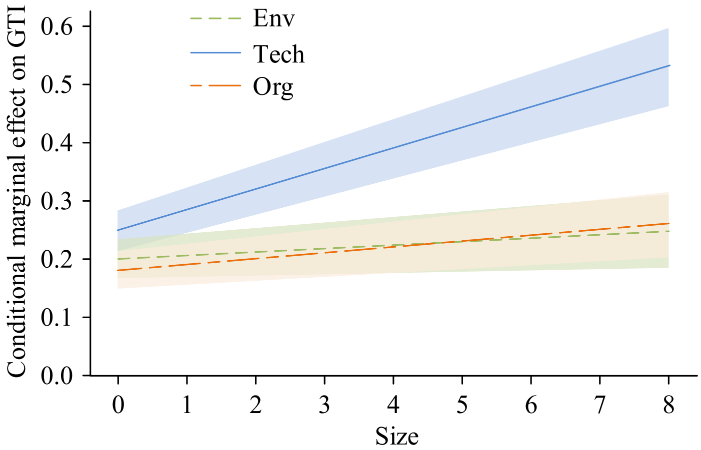


**Fig. 2.** Marginal effect curve

Note: Firm size is treated as a continuous moderator (Size = ln(Employees)); 95% confidence intervals are based on 1,000 bootstrap replications, and an effect is significant when the band excludes zero.

In Fig. 2, firm size amplifies the conditional marginal effects of internal TOE inputs on GTI. As Size increases from low to high, the marginal effect of Tech rises from 0.23 to 0.46, while the marginal effect of Org climbs from 0.25 to 0.41, indicating that larger organizations have greater capacity in utilizing their technology investments and organization skills in fostering green innovation results. However, there is hardly any change in the marginal effect of Env across different levels of Size, indicating that the environment-related variables, like policies and market, provide a constant external impetus regardless of the organization's size. Not surprisingly, the GTI means for small, medium, and large organizations consistently rise according to the shapes of curves (-0.12, 0.29, and 0.39, respectively).

### 4.3. Analysis of Heterogeneous Moderating Effects

In order to explore the moderating effect of firm heterogeneity on the driving mechanism of green technology innovation, group comparison analysis and interaction regression were adopted in this study. The results are shown in Fig. 3.

In Fig. 3(a), the mean GTI was -0.12 for small enterprises, 0.29 for medium enterprises, and 0.39 for large enterprises, indicating that larger firms had higher green technology innovation levels. This supported the scale-related moderation effect proposed in H1. For the regression analysis, the coefficient of the interaction term, namely Tech × Size, is positive, implying that technological investment had a higher impact on large organizations. For state-owned enterprises in Fig. 3(b), the mean value of GTI is 0.28 compared to that of private enterprises, which is 0.09. This means that state-owned enterprises experience stronger political restrictions and responsibilities towards society and have higher levels of green innovation awareness than private firms. Nevertheless, the interaction term for Ownership and Tech is insignificant in the interaction regression, meaning that both ownership forms are equally affected by the level of technological investment. These results partially supported H2, suggesting that ownership differences created gaps in initial resource allocation or policy response capacity. In Fig. 3(c), enterprises in eastern regions have a mean GTI score of 0.26, which is higher compared to those in other regions, where it is just 0.11, implying that there were greater policy encouragements and demands in the eastern region. Regression analysis results indicated that although the interaction between Tech and Region did not show significance, the positive role played by Env was significantly higher for firms in eastern regions. In Fig. 3(d), Env showed a weak positive correlation with GTI, and most samples concentrated in the middle range, suggesting a diminishing marginal effect of environmental factors on innovation. Such non-significance may stem from nationwide convergence in environmental compliance requirements and significant agricultural support policies, which reduce the institutional variance that could otherwise differentiate ownership types and regions. In addition, the cross-regional nature of supply chain logistics and platform market entry will make the technological and demand exposures homogeneous for organizations, leading to less region-based heterogeneity in the TOE model. However, firm size is a strong representation of the organization's resource slack and absorption capacity, such that larger organizations can effectively convert technology input and organizational practices into innovation outputs.

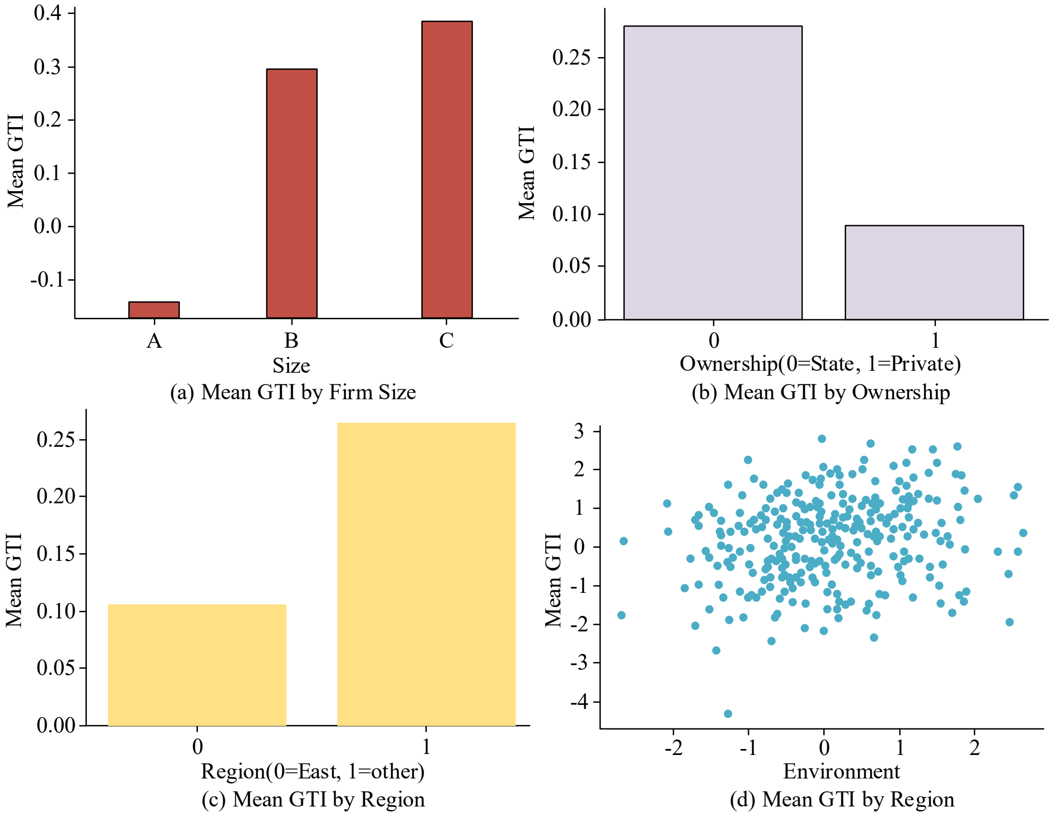


**Fig. 3.** The impact of firm heterogeneity on the GTI driving mechanism

### 4.4. Robustness Test

To test robustness, alternative variables were used. Replacing the dependent variable with the green revenue ratio or green technology investment intensity yielded consistent results, as shown in Table 4.

**Table 4.** Robustness test comparison

| Model | Tech | Org | Env |
|---|---|---|---|
| Original OLS regression | 0.441*** | 0.231*** | 0.246*** |
| Alternative dependent variable (Green revenue share) | 0.423*** | 0.218*** | 0.239*** |
| Alternative dependent variable (Green investment intensity) | 0.407*** | 0.378*** | 0.436*** |
| Negative binomial regression | 0.378*** | 0.201*** | 0.228*** |
| OLS with additional controls | 0.436*** | 0.229*** | 0.241*** |

In Table 4, the regression results align with those in Table 5, indicating that the findings do not depend on the calculation method for green patents. Moreover, negative binomial regression for dependent variables of count type is valid and does not influence the outcomes. Introduction of extra control variables, for example, economic development of the region and competition within an industry, does not affect the signs or values of key regression coefficients.

## 5. Discussion and Suggestions

### 5.1. Discussion

This study, grounded in the TOE framework, indicates that technological, organizational, and environmental factors jointly drive GTI in agricultural enterprises. However, the technological dimension exhibits a stronger decisive role in the agricultural context, suggesting that under constraints characterized by "high technological barriers and long payback periods," firms' technological accumulation and R&D capabilities constitute the critical prerequisite for initiating GTI and sustaining iterative upgrading. This result is congruent with the findings of Yin (2023) showing that digitalization facilitates innovation; however, it also takes into account industrial differences, where, for instance, in agriculture, when the forces of pressure from outside are not enough to absorb with technological competence, the power of incentive policies and markets becomes significantly less effective. Contrasting with this, according to Lou et al. (2025), government subsidies become significantly more important in pollution-intensive industries. Thus, a more realistic explanation would be to view technological competence as the “driving wheel” while organizational and environmental factors act as “absorption-acceleration-calibration.”

Heterogeneity analyses further show that firm size significantly amplifies the effect of technological factors, whereas ownership type and regional differences, although observable at the mean level, yield insignificant interaction terms, implying that they do not constitute robust “structural moderators.” This is in line with the configurational theory, which stresses “equifinality (multiple means of achieving the same result), implying that GTI can be realized by using diverse combinations of factors, instead of having a single most effective combination of factors (Liu et al., 2024; Han et al., 2025). Specifically, in an agricultural context, the homogeneity of relevant regulations and subsidies, along with more robust cross-regional business activities, can collectively reduce the extent of institutional heterogeneity, resulting in diminishing the significance of ownership and regional characteristics as moderators.

Furthermore, organizational elements have been observed to favor GTI but exhibit the law of diminishing marginal returns, thus implying that organizational development cannot be subjected to limitless linear investment. After reaching a certain point in terms of governance and human capital, it becomes more probable that additional “organizational intensification” will turn out to be wasteful costs rather than gains. In this case, more attention should be paid to complementarity between the two aspects. This finding contrasts with Le’s (2025) results in the energy sector, where no moderating role of organizational factors was identified, and is closer to the “technology–organization driven” configurational interpretation proposed by Li and Che (2024). The key contribution of organizational capability lies in providing a stable platform and resource support for technological innovation; only when the two are coupled can higher innovation performance be fully realized.

Even though China is the empirical context of the study, the reasoning embedded in the TOE framework can be extended to analyze agricultural firms operating in other geographical locations, since the TOE framework highlights a general process by which internal capabilities and external forces together influence innovation in green technologies. In developed economies, where regulatory systems and digital infrastructure are mature, the framework can be used to examine whether organizational capability and technology integration become more important than policy pressure. In developing economies, where firms often face stronger financing constraints and weaker access to green technologies, the same framework can help identify whether technology availability, public support, and institutional incentives act as the main triggers of green innovation. Therefore, the contribution of this study lies not only in its Chinese evidence but also in providing a transferable analytical framework that can be adapted to different institutional settings, agricultural structures, and stages of green transition.

### 5.2. Policy Suggestions

Based on the findings, the study proposed four recommendations: Foster innovation capacity by integrating capability gap-filling with diffusion-enabled entry barriers. Boost efforts to develop innovative solutions in important areas of green technology and digital infrastructure (green input substitution technology, energy and emission-saving devices/equipment, precision farming technologies, and smart monitoring and control systems), along with the use of instruments, including higher R&D tax credits, prizes for using innovative technologies for the first time, insurance for green technologies, and subsidized interest rates for loans. Simultaneously, set up generic technology centers and pilot test/evaluation centers at the regional level to enable technology transfers from the institute sector and the leading agrifood firms to the SME sector.

Enhance the effectiveness of policy and market incentives through “organizational coordination for efficiency” and “rule-based environmental certainty,” while avoiding organizational redundancy. At the firm level, strengthen green-innovation governance and talent systems, but focus on organizational capabilities aligned with technological investment (process reengineering, project-based R&D, and performance/incentive mechanisms) to prevent rising coordination costs from excessive management. At the policy level, improve stability and predictability by keeping regulatory standards, subsidy rules, and evaluation/acceptance criteria as consistent and transparent as possible, and implement tiered support: provide more public services and capability-building measures for smaller firms (testing and certification, training, data support, and compliance consulting), while guiding larger firms to play a supply-chain anchor role through green procurement, collaborative emission reduction, technology spillovers, and diffusion.

## 6. Conclusion

### 6.1. Research Conclusions

This study extends the TOE framework to the context of GTI in agricultural enterprises by developing and empirically testing an integrated technology–organization–environment model. Firm size is positively associated with GTI and significantly strengthens the impact of technological factors, revealing a scale-related amplification mechanism in green innovation, revealing an amplification mechanism of “scale-resources-organizational learning” in green innovation. In contrast, ownership type and regional differences do not exhibit robust moderating effects, suggesting a degree of commonality in GTI drivers across firm types. At the same time, the organizational dimension shows diminishing marginal returns, indicating that the contribution of organizational capability is not indefinitely linear.

From a policy perspective, priority should be given to enhancing firms’ access to and absorptive capacity for technologies by reducing the costs of adoption and iteration through R&D incentives, green equipment upgrading, and the diffusion of digital and low-carbon technologies. Organizational capability should be strengthened as an “absorptive platform,” guiding firms in building stable support for green technologies across talent, processes, data, and management systems. For SMEs, it is necessary to provide focused financial tools as well as increase the range of services offered by the public sector, along with demonstration-driven mechanisms for knowledge diffusion. In this sense, the implications are compatible with China's Rural Revitalization Strategy and its strategy towards modernization in the agricultural sector through accelerated green and digital transformation of agri-food supply chains.

For managers, the findings imply changes in at least three decision processes. First, innovation decision-making should shift from short-term compliance-oriented budgeting to capability-oriented investment screening, with greater emphasis on whether a technology can be absorbed, integrated, and scaled within the firm. Second, resource-allocation decisions should focus more on the alignment between technological investment and organizational support, rather than simply increasing managerial procedures or administrative arrangements. Third, external coordination decisions should move beyond passive responses to policy pressure and instead emphasize proactive collaboration with suppliers, customers, and local governments, so that environmental constraints can be converted into innovation opportunities.

More broadly, this study implies that the innovation of green technologies in agricultural businesses must not be viewed merely as a reactive process triggered by environmental legislation. Instead, it is a dynamic interaction between technology, organization, and environment. Thus, additional external push will not yield meaningful innovation outcomes without sufficient technological absorptive capabilities on the part of firms, and excessive organizational growth without appropriate technological improvement may yield less effective results. In this regard, the key difficulty in green innovation lies in firms' ability not only to innovate but also to establish sustainable organizational capability structures.

### 6.2. Limitations and Future Research Directions

There are three shortcomings still in place. First, there seems to be an issue with measuring the GTI and TOE factors, as they depend primarily on available data and statistics on these aspects. Second, although many control variables are used, the problem of endogeneity and reverse causality remains. Third, regional and ownership heterogeneity are crude, failing to recognize differences generated by the firm's position in the value chain, the intensity of policy implementation, and differences in market structures. Future research should prioritize micro-level longitudinal data and adopt more rigorous causal identification methods; additionally, it can evaluate effective pathways of GTI from a "multi-factor configurational synergy" perspective by using structural Eq. modeling (SEM) to test latent constructs and mediating/interaction relationships, and qualitative comparative analysis (QCA/fsQCA) to identify sufficient configurations of technological, organizational, and environmental conditions, thereby improving the granularity and generalizability of mechanism explanations.

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### Institutional Review Board Statement

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### Declaration of Artificial Intelligence (AI) Tools

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**Appendix**

**Table A.** Anonymized example records from the collected dataset **Panel A.** Example firm records

| Firm ID | Region | Ownership | Sub-industry | Employees | Firm age | Leverage | Green patent applications |
|---|---|---|---|---|---|---|---|
| A01 | East | State-owned | Processing | 612 | 18 | 0.54 | 8 |
| A02 | Central and West | Private | Crop cultivation | 86 | 7 | 0.41 | 0 |
| A03 | East | State-owned | Livestock breeding | 243 | 11 | 0.47 | 3 |
| A04 | Central and West | Private | Processing | 358 | 22 | 0.62 | 5 |

**Panel B**. Corresponding coded variables used in the empirical analysis

| Firm ID | Size category | GTI | Tech | Org | Env |
|---|---|---|---|---|---|
| A01 | 3 | 2.197 | 1.21 | 0.88 | 0.64 |
| A02 | 1 | 0.000 | -0.73 | -0.58 | -0.36 |
| A03 | 2 | 1.386 | 0.32 | 0.15 | 0.41 |
| A04 | 2 | 1.792 | 0.67 | 0.94 | 0.28 |