

The role of innovation and technology in achieving sustainability in China's private enterprises

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Abstract: This study explores the pivotal role of innovation and technology in fostering sustainability within China's private enterprises. Given their substantial contribution to the national economy, these enterprises are at the forefront of embracing digital transformation as a strategy for long-term growth. However, despite advancements in technology, challenges such as leadership gaps, insufficient performance evaluation, and resource constraints hinder their full potential. The research focuses on how emerging technologies—particularly digital tools such as artificial intelligence, big data, and information systems—can drive innovation while aligning with sustainability goals. The findings highlight that digital transformation not only enhances operational efficiency but also fosters innovative practices that contribute to sustainability. Additionally, government innovation policies and financial incentives are critical in facilitating this transition. The paper concludes by offering strategic recommendations for private enterprises to integrate technology and innovation to overcome existing challenges, thereby enhancing their competitiveness and promoting sustainable business practices.

Keywords: Digital transformation, Innovation capability, Private enterprises, Sustainability, Technological innovation.

1. Introduction

As China accelerates its pursuit of sustainable development, innovation and advanced technologies have become central to transforming its private enterprise sector. Emerging digital technologies—such as big data, artificial intelligence, and next-generation information systems—are not only reshaping economic structures but also serving as catalysts for sustainable business practices. The integration of digital tools into traditional industries is fostering the evolution of a digitally empowered economy, one that enhances productivity, optimizes resource allocation, and reduces environmental footprints. Since the formal inclusion of the digital economy into China's national strategy in 2017, the sector has expanded rapidly, accounting for a significant share of the country's GDP by 2020. This shift marks a critical phase in aligning economic development with ecological and technological sustainability [1].

Private enterprises, which form a vital part of China's market economy, are increasingly embracing digital transformation to stay competitive and responsive to evolving market demands. This wave of technological adoption is not merely about upgrading systems but involves a fundamental rethinking of organizational processes, decision-making frameworks, and innovation pathways. As digital platforms become embedded into business ecosystems, firms are witnessing shifts in operational logic, value creation models, and management structures. The "Digital Technology+" approach has emerged as a strategic direction, offering private enterprises an avenue to transition toward greener, smarter, and more resilient business models [2].

Despite these advancements, the journey toward full-scale digital transformation is fraught with complexity. Many private firms remain in an early or fragmented stage of technological adaptation,

often hindered by limited technical capabilities, talent shortages, and capital constraints. Compared to state-owned enterprises, private firms face additional hurdles in accessing innovation resources, which complicates their efforts to adopt sustainable practices through technological means. Although digital transformation has been linked to increased innovation potential, the mechanisms through which it fosters sustainable innovation in private enterprises remain underexplored [3].

Government support plays a crucial role in bridging these gaps. While market forces drive much of the innovation momentum, policy intervention is essential to address systemic challenges. Financial incentives, regulatory support, and the creation of innovation-friendly ecosystems can significantly boost private firms' ability to integrate technology for sustainable outcomes. Policies tailored to enhance transparency, reduce operational uncertainty, and improve access to finance are especially relevant in this context [4].

In light of these dynamics, this study investigates how digital transformation can drive innovation that aligns with sustainability goals in China's private enterprises. It further evaluates the influence of government innovation policies on facilitating this transformation. The study contributes to the field in four key ways. First, it provides empirical insights into the effects of digital transformation on sustainable innovation within private firms. Second, it examines the role of innovation-driven policy incentives in enabling this process. Third, it identifies internal and external factors—including regional digital economy development and enterprise scale—that influence the success of transformation. Lastly, it outlines four strategic pathways through which digital innovation enhances enterprise sustainability: increasing information transparency, mitigating operational risks, easing financing barriers, and boosting productivity. Collectively, these findings offer valuable guidance for promoting sustainable innovation in China's rapidly evolving private sector [5].

2. Methodology

The dependent variable in this study is the level of innovation within private enterprises, which we define as enterprise innovation (Innovn). Innovation within a company can be assessed through various indicators. One common approach measures the company's investment in research and development (R&D), while another approach uses the number of patents filed as a proxy for the output of innovation activities. In the context of assessing innovation in Chinese private enterprises, research indicates that the use of patent data as a metric provides a clearer reflection of a company's true innovation capabilities compared to merely evaluating R&D spending. To further refine this measure, this study specifically focuses on invention patents due to their higher technical complexity, serving as a more accurate indicator of an enterprise's innovation potential. For this analysis, we measure innovation by taking the natural logarithm of the number of invention patent applications, with an addition of one to ensure all values are positive.

3. Independent Variables

The independent variables in this research are digital transformation (Dt) and innovation incentive policy (Sub). Digital transformation has become a key driver in the pursuit of sustainability and innovation within China's private sector. This study employs a Python-based crawler to collect the annual reports of private listed enterprises, extracting digital transformation-related keywords from the PDFs using the Java PDFBox library. The frequency of relevant terms is then analyzed and logarithmically transformed to form a digital transformation index. In addition to digital transformation, innovation incentives—such as government subsidies—play a pivotal role in supporting sustainable practices within businesses. To quantify this, subsidy information from the companies' financial statements, particularly under the category of “Non-Operating Income,” is extracted and processed. The data is refined by manually screening and calculating the relevant subsidy values, based on the total assets of the companies.

4. Control Variables

Several control variables are incorporated based on existing literature and the specific institutional context of China's private sector. These variables account for factors that could influence the innovation activities of private enterprises, such as company size (Size), asset turnover (Ato), cash flow ratio (Cashflow), growth rate of operating income (Growth), dual listing status (Dual), listing age (ListAge), institutional shareholding ratio (Inst), and whether the company is audited by a Big Four accounting firm (Big4).

5. Research Model

Model 1 tests the relationship between enterprise innovation (Innovn) and digital transformation (Dt) as the primary explanatory variable, formulated as in Formula (1). Building upon this, Model 2 introduces an interaction term between digital transformation and innovation incentives ($Dt \times Sub$) to examine how these two factors jointly influence innovation.

6. Results and Discussion

This study utilizes a panel dataset covering the period from 2011 to 2020, focusing specifically on listed private enterprises in China. The data are extracted from reputable financial databases that track corporate performance and accounting disclosures. To ensure the reliability and accuracy of the empirical analysis, several data-cleaning steps were undertaken. First, enterprises in sectors with distinct financial reporting standards, such as finance and insurance, were excluded. Second, firms designated as ST or *ST—often signaling abnormal financial conditions—were removed to avoid distortions. Third, entries with missing or outlier financial values were eliminated, retaining only enterprises with at least five consecutive years of valid data. Lastly, all continuous variables were winsorized at the 1st and 99th percentiles to minimize the influence of extreme values (Figure 1). These steps resulted in a refined dataset comprising 7,505 firm-year observations suitable for regression analysis [6].

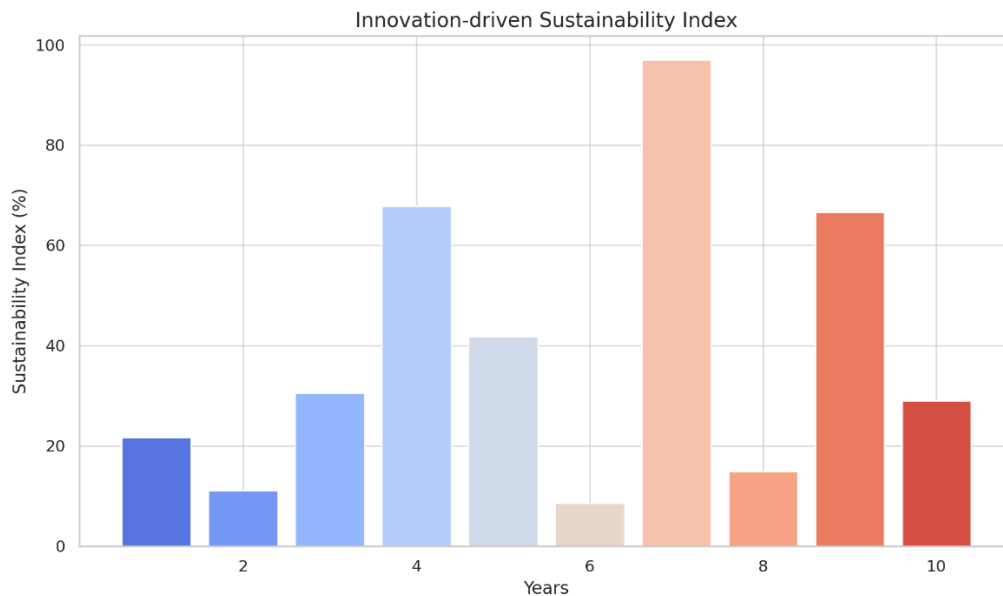


Figure 1.
Innovation-driven Sustainability Index.

The summary statistics reveal considerable variation across core variables. The innovation index for enterprises ranges from 0 to 11.04, with a standard deviation of 1.529, suggesting pronounced differences in innovation efforts among private firms. Similarly, digital transformation shows a wide range, from 0 to 4.635, with a relatively low mean value of 1.398. This indicates that although some firms have made notable progress, the overall level of digital transformation among private enterprises remains modest. Innovation incentives—measured in terms of government support or policy-driven benefits—also exhibit significant disparity, ranging from 0 to 3.487. This variation underscores the uneven distribution of external support available for private firms pursuing technological innovation and sustainable practices [7].

The regression results confirm a statistically significant relationship between digital transformation and innovation within China's private sector. In the initial model without control variables, the coefficient for digital transformation is 0.139, significant at the 1% level. Upon introducing control variables, the coefficient increases to 0.166, remaining robust and significant. These findings support the hypothesis that digital transformation positively contributes to private enterprises' innovation capabilities, particularly in terms of R&D investment and technological advancement. Further analysis explores the interaction effect between digital transformation and innovation incentives. The interaction term shows a positive effect on innovation outcomes, with coefficients of 0.021 (without controls) and 0.030 (with controls), the latter being significant at the 10% level. This suggests that the presence of innovation incentives can amplify the benefits of digital transformation, helping firms overcome operational constraints and enhance their innovation output. Particularly for small and medium-sized private enterprises—which often face higher operational risks and limited access to economies of scale—government support plays a critical role in offsetting risk and encouraging greater investment in sustainable innovation [8].

To better understand the role of digital transformation in fostering sustainable innovation among private enterprises, this study investigates whether its effects vary depending on regional economic conditions and firm-specific characteristics. Given the diversity of China's economic landscape, factors such as geographic location, the maturity of the local digital economy, and enterprise size may influence how effectively digital transformation translates into innovation outcomes. As such, firms are grouped based on three dimensions: regional distribution (eastern, central, and western provinces), local digital economy development (high versus low), and firm scale (large versus small, using the median asset size as a benchmark) (Figure 2). This stratified approach allows for a nuanced assessment of how innovation gains through digital transformation differ across contexts [9].

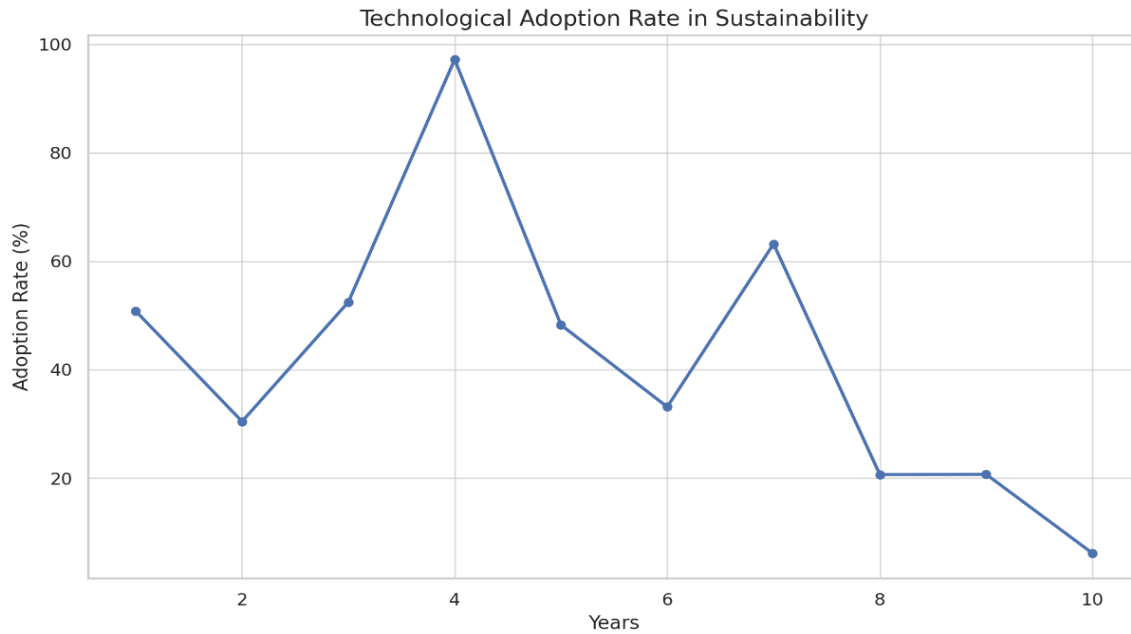


Figure 2.
Technological Adoption Rate in Sustainability.

The analysis reveals that digital transformation significantly enhances innovation among private enterprises in all regions, though with varying degrees of impact. Enterprises in the eastern region benefit the most, with the innovation effect statistically stronger than in central or western regions. This regional gap may stem from differences in economic development and technological infrastructure. Firms in the more industrialized eastern provinces typically face greater competitive pressure, compelling them to embrace digital tools more rapidly. In contrast, central and western regions often lag in network readiness and technical capacity, which may slow down transformation efforts and limit innovation potential. As such, the more dynamic economic conditions and advanced digital ecosystems in the eastern provinces amplify the innovation gains from digitalization, contributing to more sustainable business models [10].

Firms situated in areas with a more developed digital economy also experience a stronger link between digital transformation and innovation. Regardless of the region's digital maturity, digital transformation has a statistically significant and positive impact. However, enterprises operating within robust digital economies benefit more, likely due to superior infrastructure, wider access to digital services, and a more vibrant ecosystem of digital talent and innovation culture. These advantages create a supportive environment that enables private firms to better leverage digital tools for strategic transformation, process optimization, and sustainability-focused innovation [11].

The third dimension of heterogeneity analysis focuses on the scale of enterprises. While both large and small firms benefit from digital transformation, the innovation effect is more substantial in larger firms. This finding is consistent with the idea that larger organizations are better positioned to absorb the costs and risks associated with technological innovation. Their greater access to financial resources, managerial expertise, and operational scale allows them to more effectively integrate digital technologies into their value chains. As a result, large private enterprises can more readily translate digital transformation efforts into sustainable innovation outcomes, reinforcing their market competitiveness and long-term viability. To further examine how innovation incentives and digital transformation interact to influence sustainable innovation, this study investigates the heterogeneity of their combined effects across regions, digital economy development levels, and firm size. The results

reveal meaningful differences in how supportive policies and technological upgrades work together to drive innovation in private enterprises [12]. In the eastern region, where the digital infrastructure is more mature and innovation ecosystems are well-established, the joint effect of innovation incentives and digital transformation on enterprise innovation is statistically significant. These regions benefit from superior technological capabilities, abundant digital talent, and robust public support mechanisms. The alignment between government subsidies and enterprise-level digital strategies enhances firms' ability to upgrade sustainably and innovate efficiently. In contrast, this synergy is less evident in central and western regions, where weaker infrastructure, limited human capital, and a less conducive policy environment reduce the effectiveness of incentive policies in reinforcing digital-led innovation.

Interestingly, the collaborative effect between innovation incentives and digital transformation is more pronounced in areas with lower levels of digital economy development. In such regions, where firms typically face greater barriers to accessing digital tools and capabilities, government subsidies appear to play a compensatory role. By reducing financial constraints and mitigating the risks associated with innovation failure, these incentives effectively bridge resource gaps and catalyze digital adoption. This in turn strengthens the innovation capacity of enterprises that otherwise might lag behind due to systemic disadvantages. Conversely, in more digitally developed areas, where enterprises already possess sufficient internal resources and access to technology, the marginal impact of external innovation incentives diminishes [13].

The final dimension of analysis focuses on enterprise size. Results indicate that the synergistic effect of innovation incentives and digital transformation is far more significant for small-scale private enterprises than for their larger counterparts. Smaller firms, often constrained by capital limitations and higher risk exposure, face substantial hurdles in pursuing innovation independently. While digital transformation can alleviate operational inefficiencies, its benefits may take time to materialize [14]. Here, government support provides immediate relief by injecting financial resources into R&D and innovation activities, effectively enabling small firms to sustain transformation initiatives. In contrast, large firms, with more stable cash flows and diversified operations, tend to rely less on external incentives to fund innovation, thus reducing the relative impact of policy support on their digital strategies (Figure 3).

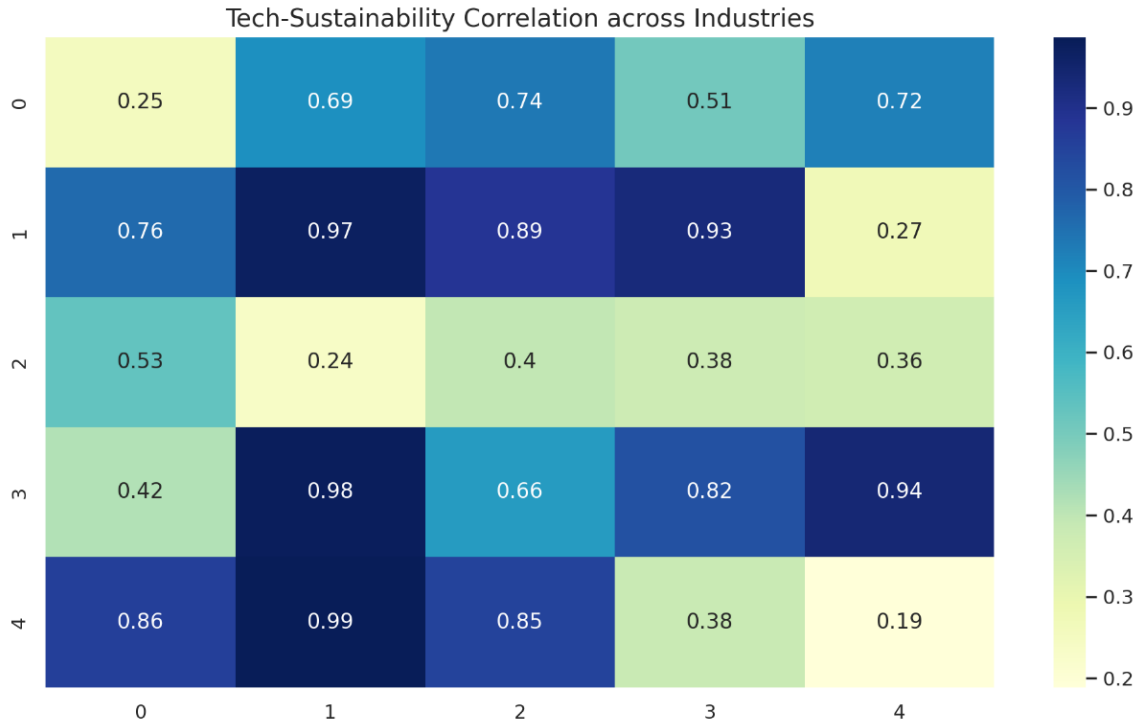


Figure 3.
Tech-Sustainability Correlation across Industries.

To reinforce the credibility of the empirical analysis concerning how innovation and technological advancement support sustainability goals in China’s private sector, a series of endogeneity and robustness evaluations are carried out. First, a lagged version of digital transformation is adopted as an instrumental variable to address potential endogeneity concerns. The statistical strength of the instrument is confirmed by an F-statistic minimum eigenvalue far exceeding conventional thresholds, demonstrating its suitability in mitigating weak instrument bias. Next, a two-stage analytical approach is employed to examine the consistency of digital transformation’s influence on sustainable innovation outcomes. Firms are classified based on the median level of digital engagement, creating a binary variable representing digital transformation intensity. This index is then used in a probit model, which reveals a statistically significant and positive relationship—further reinforcing the study’s main conclusions.

To deepen the analysis, a propensity score matching technique is used to correct for sample selection bias. The binary digital transformation indicator is treated as the dependent variable, while key firm-level controls—such as size, asset turnover, liquidity, growth rate, governance structure, listing age, institutional presence, and audit quality—serve as matching variables. A 1:1 nearest-neighbour approach is adopted. The results continue to affirm the strong and positive impact of technological change on firm-level innovation capacity.

To ensure the reliability of findings related to the role of technology in driving sustainable innovation, several robustness tests are conducted. First, instead of relying on a single innovation metric, a composite patent count—encompassing invention, utility, and design patents—is used as a proxy for innovation performance. Secondly, the firm’s digital maturity is measured by the proportion of digital-related intangible assets within their total intangible asset portfolio, sourced from year-end disclosures in financial statements. This alternative metric serves to revalidate the influence of technological initiatives on long-term innovation efforts. Third, to minimize potential distortion from sectors inherently characterized by digital orientation, samples from industries naturally predisposed to

technology adoption are excluded from the analysis. Finally, to account for the temporal dimension of digital transformation's benefits, a lagged term of digital transformation is introduced into the primary model. The outcome remains consistent, indicating that the positive influence of technological adaptation on sustainable innovation is both stable and persistent across various model specifications.

To further understand how technological and digital initiatives contribute to sustainable innovation within China's private enterprises, this section investigates the internal pathways through which digital transformation exerts its impact. Specifically, intermediary models are developed to test whether such transformation enhances transparency, reduces operational volatility, eases financing constraints, and improves total factor productivity—each of which may serve as a bridge to sustainable innovation outcomes.

Digital adoption in private firms can significantly improve the visibility and clarity of operational and financial data. This transparency allows external stakeholders to better assess company performance and encourages internal governance improvements. In turn, this creates a conducive environment for sustained R&D and innovation. As a proxy for transparency, the number of financial analysts actively following a firm is used, expressed logarithmically. Regression analysis reveals a consistently strong and positive relationship between digital transformation and analyst coverage, indicating enhanced transparency. Furthermore, the link between digital transparency and innovation remains significant when both variables are included, suggesting that improved transparency is one of the channels through which digitalization boosts innovation [15].

Digital technologies also help private enterprises manage uncertainties more effectively. By streamlining workflows, enabling data-driven decision-making, and facilitating inter-firm coordination, digital tools reduce exposure to operational risks. This is particularly relevant for sustainability-oriented innovations, which often require risk-taking and iterative experimentation. Operational risk is proxied by the three-year fluctuation in return on assets. A negative and significant coefficient supports the claim that digital initiatives help mitigate operational uncertainties, while the relationship between digital transformation and innovation remains intact—highlighting operational risk reduction as another vital mechanism (Figure 4).

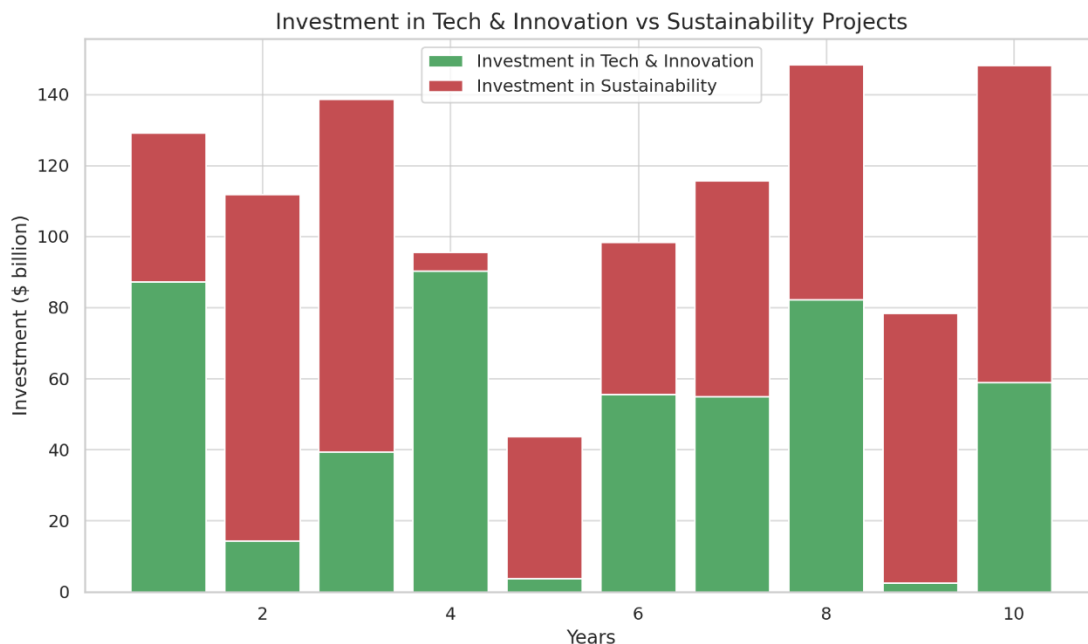


Figure 4.
Investment in Tech & Innovation vs Sustainability Projects.

Technological advancements in digital platforms also contribute to bridging information gaps between firms and external investors. By improving financial disclosures and communication, digital transformation builds trust and reduces perceived investment risks. This can lead to better access to funding, preferential policy treatment, and improved stakeholder relationships. A composite index reflecting financing constraints indicates that digital transformation has a positive influence in loosening capital barriers. Even after incorporating the constraint index, the effect of digital transformation on innovation persists, implying that easing capital pressure is a key facilitator in the innovation process. Finally, one of the most profound effects of digital transformation lies in optimizing resource allocation and boosting productivity across firm operations [16]. By leveraging advanced analytics and digital platforms, enterprises can increase both the efficiency and effectiveness of input usage, leading to greater output per unit of resource. Using an econometric model based on a production function approach, total factor productivity is measured and found to be significantly influenced by digital adoption. The sustained significance of this relationship—both with and without the inclusion of productivity metrics—confirms that improved operational efficiency plays a central role in enabling private firms to pursue sustainable, innovation-driven growth.

7. Conclusion

In conclusion, the integration of innovation and technology within China's private enterprises is essential for achieving sustainability and long-term success. Digital transformation plays a crucial role in improving operational efficiency, fostering innovation, and aligning business practices with sustainability goals. Despite the promising potential of technological advancements, the journey towards full digital integration is not without its challenges, particularly for small and medium-sized enterprises. The study underscores the importance of government support, particularly through innovation incentives and financial subsidies, to bridge the gaps in technological capabilities and resources. It is evident that both digital transformation and supportive government policies can significantly enhance the innovation capacity of private enterprises, particularly in regions with less developed digital economies. By leveraging digital tools and aligning them with sustainable practices, China's private sector can not only improve its competitiveness but also contribute to the nation's broader sustainability objectives.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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