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Digital Transformation as a Catalyst for Innovation in Singaporean Startups: Econometric Evidence from Patent Outputs and R&D Investment

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Abstract

This study examines the impact of digital transformation on innovation in Singaporean startups, using patent applications and R&D expenditure as quantitative indicators. An Autoregressive Distributed Lag (ARDL) model is applied to time-series data (2015–2025) to capture both short- and long-run dynamics. The results reveal a significant long-run elasticity of 0.78 between R&D investment and patent output, indicating efficient conversion of digital inputs into innovation. Government grants and venture capital also exert positive effects, with elasticities of 0.35 and 0.42, respectively. The implementation of the RIE2025 innovation strategy is associated with a 28% increase in patenting activity. The error-correction term suggests rapid adjustment, correcting 52% of disequilibria annually. These findings highlight the effectiveness of Singapore's integrated innovation ecosystem and provide policy-relevant insights for fostering digital-driven entrepreneurship.

Keywords: Digital transformation; startup innovation; patent analysis; R&D expenditure; Singapore; ARDL model; RIE2030; innovation policy.
JEL Classification: O31, O32, C32, O38.

1. Introduction.

For decades, economic development was primarily attributed to traditional production factors—land, labor, and capital. However, Schumpeter (1911/1934) argued that innovation, rather than these factors, is the principal driver of economic growth. Novel ideas can generate new economic opportunities, reshaping market structures and initiating cycles of growth and disruption. His concept of "creative destruction" (1942) highlights how innovation replaces existing structures with more efficient ones, whether through new products, resource utilization, or organizational changes (Fagerberg, 2003; McCraw, 2007).

Innovation is central at multiple levels. At the macroeconomic level, it drives growth and employment (Boparai & Kaur, 2025; Christensen, 1997; Damanpour, 1991). Politically, it informs industrial and technological policies (Burgelman & Maidique, 1988). Socially, it addresses pressing societal challenges through novel products and services (Chesbrough, 2003). Organizationally, innovation enhances enterprise sustainability, adaptability, and performance, particularly when technological capabilities are present (Fagerberg et al., 2013; Martin, 2013).

The rapid diffusion of digital technologies—artificial intelligence, cloud computing, big data, and robotics—has further transformed innovation processes. Studies show these technologies enhance productivity, support industrial transformation, and enable new knowledge creation (Jiao et al., 2025; Wipatkrut & Su, 2025; Zolas & Haltiwanger, 2025). Consequently, enterprises increasingly adopt digital solutions, restructuring operations, business models, and strategic planning to sustain competitiveness (Vial et al., 2019; Gong & Ribiere, 2021; BMWi, 2015). Startups, in particular, benefit from enhanced flexibility, rapid experimentation, and global scalability (CIO, World Asia, 2025).

Empirical studies have examined how digitalization impacts innovation in the United States and China, using patent data and digital economy indicators to evaluate performance (Jung et al., 2025; Chen, 2025; Pu, 2025; Minijiang & Brychko, 2025; Zhao & Wang, 2025; Guo et al., 2021). Yet, despite available data, research on Singaporean startups remains limited. This study addresses this gap by quantifying the effects of digital R&D spending, government grants, and venture capital on patent-based innovation in Singapore from 2015 to 2025, using an integrated econometric model rather than qualitative case analyses.

2. Literature Review and Conceptualised Hypotheses

2.1. The relationship between spending on digital transition and startup innovation

Numerous studies across countries emphasize the necessity for enterprises to adopt digital transformation to achieve competitive advantages. Empirical evidence shows that investment in digital R&D significantly enhances innovation capabilities across diverse types of enterprises (Khin & Ho, 2019; Hanelt et al., 2021; Warner & Wager, 2019; Verhoef et al., 2021; Vial, 2019; Zhi-Guang Li et al., 2024; Li Chen et al., 2024). Similarly, Cui (2025) highlights the role of digital investment in fostering sustainable innovation and improving technological knowledge. In the Chinese context, Zhu and Manansala (2024) detail the mechanisms through which digitalization drives enterprise-level innovation, while Gupta et al. (2024) demonstrate that digitalization enhances R&D quality, thereby increasing innovation outputs.

Patent indicators are widely used to measure innovation performance. Zhang and Wang (2024), in a systematic review, show that digital transformation spending is a critical driver of knowledge creation and innovation, often evidenced by patent accumulation. In startups, small, and medium enterprises, digital R&D investments significantly boost patenting activity. For instance, Marin et al. (2023) analyzed 1,190 Spanish enterprises, revealing that digital R&D accelerates the introduction of patents and technological innovations across the value chain. Similarly, Cen and Lim (2025) confirm a positive association between investments in advanced digital technologies—such as AI and cloud computing—and patent output, indicating higher innovation productivity. Recent studies by Jiang et al. (2023) and Chen & Guo (2024) further support that digital R&D investment not only increases patent quantity but also enhances technological innovation quality in startups.

Based on this evidence, the study proposes the following hypotheses:

H1: *There is a long-term equilibrium relationship between digital transformation spending and patent output in Singaporean startups.*

H2: *Digital R&D investment positively influences patent registration over time.*

2.2. The role of government programs in supporting digital transformation in enhancing innovative efficiency

In 2024, the world's largest patent-producing countries were China, with over one million patents granted, followed by the United States (319,815 patents) and the European Union (109,524 patents). Empirical evidence from these leading economies demonstrates a significant relationship between government support and innovation efficiency, often reflected in increased patent outputs among enterprises and startups.

In large enterprises, studies of health and pharmaceutical companies in the United States and China confirm that government support positively affects patent generation (Azoulay et al., 2019; Xia et al., 2023). For instance, Azoulay et al. (2019) quantified that every $10 million in subsidies to the National Institutes of Health (NIH) corresponded to an increase of 2.7 patents. Similar effects have been observed in European institutions (Charnitsky & Cindy, 2019), U.S. universities (David et al., 2020), and Italian organizations (Bronzini & Lacina, 2014).

For small enterprises and startups, research in the United States, Europe, and China shows a strong positive association between government support—whether at the inception or growth stage—and innovation performance, including patent quantity and quality (Fredeco et al., 2014; Howell, 2017, 2020; Howell & Brown, 2020; Lerner, 2018). Comparative studies in Dubai (Walsten, 2018) and the U.S. (Howell, 2017) indicate that startups benefiting from government programs exhibit higher patenting activity than those without support.

Based on this evidence, the third hypothesis of this study is proposed:

H3: Government programs supporting digital transformation enhance the efficiency of converting innovation inputs into outputs in Singaporean startups.

3. The research paper methodology

This study falls within the category of applied econometric research. It employs an analytical approach to examine key variables and utilizes the Autoregressive Distributed Lag (ARDL) model to test hypotheses and estimate quantitative relationships. The ARDL framework is particularly suitable for analyzing short time-series data, covering 11 years. This methodological choice aligns with prior research applying ARDL for similar purposes, including studies by Silva, Moutinho, & Oliveira (2024), Paiola & Gebauer (2020), Galindo-Martín (2023), and Josheski & Koteski (2011).

3.1. The study, population and sample

- **The study population**

Singapore-based startups operating in the digital technology sector benefit from the aggregated annual data.

- **The data resources:**

This research paper uses many reliable sources to extract valuable data.

Table 1. (The data sources) presents the key variables used in the study, including their definitions, measurement units, means, standard deviations, and data sources. The variables encompass digital R&D spending, government support, venture capital investment, and patent outputs, forming the basis for the econometric analysis using the ARDL model.

Table (1): The data sources.

Variable	Primary Source	Secondary Source	Access Date	Frequency
Patents	Intellectual Property Office of Singapore (IPOS)	WIPO Statistics Database	March 2026	Annual
R&D Expenditure	A*STAR National Survey of R&D	BERD (Business Enterprise R&D) indicators	March 2026	Annual
Government Grants	Enterprise Singapore	Annual Reports of RIE2020/2025	March 2026	Annual
VC Investment	Singapore Venture Capital Association	DealStreetAsia Database	March 2026	Annual
Digital Infrastructure	Infocomm Media Development Authority (IMDA)	Global Innovation Index (WIPO)	March 2026	Annual

3.2.The Study Variables

This study investigates the impact of digital transformation on innovation performance in Singaporean startups. To this end, four key variables are considered: digital R&D spending, government support, venture capital investment, and patent outputs.

Table 2 summarizes these variables, including their definitions, units, descriptive statistics, and data sources, forming the foundation for the subsequent econometric analysis using the ARDL model.

Table (2): Variables Description

Variable	Symbol	Definition	Measurement Unit	Expected Sign	Theoretical Justification
Dependent Variable					
Patent Applications	Patentst	Number of patent applications filed by startups with IPOS annually	Count (Number of patents)	N/A	Griliches (1990); Park et al. (2025)
Independent Variables					

R&D Expenditure	RDt	Annual expenditure on research and development by digital startups	Million SGD (constant 2015 prices)	Positive (+)	Romer (1990); Zhou & Liu (2025)
Government Grants	Grantst	Value of government grants allocated to digital transformation in startups	Million SGD (constant 2015 prices)	Positive (+)	Chen (2025); Singapore EDB (2025)
Venture Capital Investment	VCt	Annual venture capital investment in digital startups	Million SGD (constant 2015 prices)	Positive (+)	signaling theory; Chen (2025)
Digital Infrastructure Index	Infrat	Composite index of digital infrastructure quality (fixed broadband, mobile, servers, cybersecurity)	Index (0-100)	Positive (+)	WIPO GII (2025); Beijing Academy of Social Sciences (2025)
Dummy Variables					
RIE2025 Dummy	*D_RIE* 2025	Implementation period of RIE2025 plan	1 for 2021-2025, 0 otherwise	Positive (+)	NRF Singapore (2025)
RIE2030 Dummy	*D_RIE* 2030	Implementation period of RIE2030 plan	1 for 2026-2025 (projected), 0 otherwise	Positive (+)	NRF Singapore (2025)

3.3. Proposed Standard Model

The study is based on the Autoregressive Distributed Lag (ARDL) model, due to its suitability for the relatively small sample size and its ability to deal with different variables in the degree of integration (I(0) or I(1)).

Software Used

EViews 13 for unit root tests, ARDL estimation, and diagnostic tests

Stata 18 for robustness checks (FMOLS, DOLS, CCR)

Microsoft Excel for data organization and preliminary analysis

The mathematical formula for the model:

Δln(Patentst)=α+i=1∑pβiΔln(Patentst−i)+j=0∑qγjΔln(RDt−j)+k=0∑rδkΔln(Grantst−k)+θ1 ln(Patentst−1)+θ2ln(RDt−1)+θ3ln(Grantst−1)+λ1DRIE2025+λ2DRIE2030+εt

Δ: Indicates the first difference.

ln: Indicates the natural logarithm of the variable.

p, q, r: Optimal lag interval lengths determined using AIC or SBC criteria.

εt: Random error limit.

3.4. Standard Analysis Steps

- **Unit Root Tests**: Using ADF and PP tests to determine the degree of time series integrity.
- **Cointegration Test**: Using bounds testing within the ARDL model to test for long-term equilibrium.
- **Model Estimation**: Estimating the correlation coefficients in the short and long runs.
- **Diagnostic Tests**: Using residual tests to ensure the model is free from autocorrelation problems (LM test), variance instability tests (ARCH test), and normality (Jarque-Bera test).
- **Structural Stability Tests:** Using CUSUM and CUSUMSQ tests to verify the stability of the model's coefficients over the study period.

4. Data analysis and discussion of results

1.1. Analysis of general trends

Growth in R&D Spending: Business enterprise R&D (BERD) in Singapore more than doubled from S$4.2 billion in 2015 to S$8.1 billion in 2025, representing a compound annual growth rate (CAGR) of 6.8% (data.gov.sg). This trend underscores the critical role of sustained funding in enhancing innovation efficiency (Zhou & Liu, 2025).

Increase in Patents: The number of patents filed by startups increased from 320 in 2015 to 890 in 2025, reflecting an annual growth rate of 10.8%. This growth highlights the impact of knowledge digitization and digital R&D investment on improving innovation outputs (Park et al., 2025).

Venture Capital Development: Venture capital inflows into deep-tech startups more than doubled over the same period, rising from S$0.5 billion in 2015 to over S$1 billion in 2025. This demonstrates the role of patent activity as a signal that attracts private investment and supports startup innovation (Chen, 2025).

Government Initiatives: Policy programs, such as AI Trailblazers, have accelerated the adoption of artificial intelligence across enterprises, yielding measurable improvements in productivity and innovation performance (Singapore Economic Development Board, 2025).

1.2. Standard analysis results

First: Unit root test results: To ensure the reliability of the ARDL model, the stationarity properties of the study variables were examined using unit root tests. Table 3, presented at the end of the paper, summarizes the results of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The results indicate that the variables are a combination of I(0) and I(1), confirming the suitability of the ARDL approach for analyzing both short- and long-run relationships.

Table 3, presents the stationarity analysis of the study variables using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The table reports the test statistics, critical values at 1%, 5%, and 10% significance levels, and the order of integration (I(0) or I(1)) for each variable, confirming the appropriateness of the ARDL model for subsequent econometric analysis.

Table (3): Unit root test

Variable	Level	First dif	Integration degree
ln(Patents)	2.31-	4.56-**	I(1)
ln(RD)	1.87-	5.12-**	I(1)
ln(Grants)	3.45-**	-	I(0)
ln(VC)	2.11-	4.89-**	I(1)

Note: **Indicates significance at the 5% level.

From (table3) the results indicate that the study variables exhibit mixed orders of integration, with a combination of I(0) and I(1). This validates the use of the ARDL (Autoregressive Distributed Lag) methodology, which can accommodate such heterogeneity in variable stationarity. The varying integration levels also reflect the inherent complexity of economic relationships underlying innovation processes, consistent with findings from Zhou & Liu (2025) and Chen (2025).

Second: Cointegration Test (Bounds Test): To examine the existence of a long-run relationship among the study variables, the ARDL bounds test for cointegration was conducted. Table 4, presented at the end of the paper, summarizes the F-statistics and critical values at the 1%, 5%, and 10% significance levels. The results indicate that the computed F-statistics exceed the upper bound values, confirming the presence of a long-run equilibrium relationship between digital R&D spending, government support, venture capital investment, and patent outputs in Singaporean startups.

Table (4): Cointegration Test (Bounds Test)

Value	Calculated value	Critical value (I(0))	Critical value (I(1))
F-statistic	**6.84**	**3.79**	**4.85**

In Table 4, the computed F-statistic of 6.84 exceeds the upper critical value of 4.85 at the 5% significance level, leading to the rejection of the null hypothesis of no cointegration. This confirms the existence of a long-term equilibrium relationship among the variables, demonstrating a stable linkage between digital transformation and innovation. These results reflect the maturity and robustness of Singapore’s innovation ecosystem and provide strong empirical support for the effectiveness of integrated R&D investments, government support, and venture capital in driving sustainable startup innovation.

Third: Estimating the relationship in the long term (Long-Run Coefficients): Following the confirmation of cointegration among the study variables, the long-run relationship was estimated using the ARDL approach. Table 5, presented at the end of the paper, reports the estimated long-run coefficients, their standard errors, t-statistics, and significance levels.

Table (5): Tests of Long-Run relationship

Variable	Coef	standard error	t-statistic	Sig level
ln(RD)	**0.78**	**0.12**	**6.50**	**0.000**
ln(Grants)	**0.35**	**0.08**	**4.37**	**0.002**
ln(VC)	**0.42**	**0.11**	**3.82**	**0.005**
D_RIE2025	**0.28**	**0.09**	**3.11**	**0.014**
C	**2.15**	**0.67**	**3.21**	**0.012**

The results indicate that digital R&D spending, government support, and venture capital investment all have significant positive effects on patent outputs, confirming their sustained impact on startup innovation in Singapore.

Interpretation of Results:

- **Research and Development (R&D) Expenditure:** A 1% increase in R&D spending is associated with a 0.78% rise in patent registrations in the long term. This high elasticity indicates an exceptionally efficient conversion of research inputs into innovative outputs. Notably, this efficiency surpasses that observed in many developed countries, where elasticities typically range between 0.5% and 0.7%. These findings align with prior research emphasizing the importance of sustained R&D investment (Zhou & Liu, 2025) and suggest that Singaporean startups are highly proficient in translating innovation inputs into tangible results.
- **Government Grants:** A 1% increase in government funding corresponds to a 0.35% increase in patent filings. This result underscores the complementary role of public financial support in alleviating capital constraints and fostering innovation (Zhou & Liu, 2025). It also reflects the effectiveness of targeted programs such as AI Trailblazers in promoting technological adoption and innovation (Singapore Economic Development Board, 2025).
- **Venture Capital (VC) Investments:** Venture capital plays a significant role in driving innovation, with a 1% increase in VC funding leading to a 0.42% rise in patent output. This relationship highlights the dual function of patents: they not only signal innovative potential to attract investment but also act as catalysts for additional funding, creating a positive feedback loop that further stimulates innovation (Chen, 2025).
- **RIE2025 Innovation Plan:** Implementation of the RIE2025 initiative, represented by a dummy variable, is associated with a 28% increase in patent filings (coefficient = 0.28). This finding demonstrates the effectiveness of strategic governmental policies in enhancing innovation performance. It is consistent with prior evidence on the critical role of supportive innovation policies (Léger, 2007) and is further corroborated by reports from the Singapore Economic Development Board (2025) and Amazon Web Services (2025), which document the success of such interventions.

Fourth: Estimating the relationship in the short term (ECM Model): Using residual tests to ensure the model is free from autocorrelation problems (LM test), variance instability tests (ARCH test), and normality (Jarque-Bera test).

Following the estimation of the long-run coefficients, the short-run dynamics were analyzed using the Error Correction Model (ECM) derived from the ARDL framework. Table 6, presented at the end of the paper, summarizes the short-run coefficients, their standard errors, t-statistics, and significance levels. The results indicate that changes in digital R&D spending, government support, and venture capital have immediate positive effects on patent outputs. The error correction term is negative and significant, confirming rapid adjustment toward the long-run equilibrium.

Table (6): Tests of Short-Run Relationship

Variable	Coef	standard error	t-statistic	Sig level

Δln(RD)	0.31	0.09	3.44	0.009
Δln(Grants)	0.18	0.06	3.00	0.017
Δln(VC)	0.22	0.08	2.75	0.025
ECM (-1)	**-0.52**	**0.11**	**4.73-**	**0.001**

The ECM coefficient is negative and significant at –0.52, indicating the existence of a long-term equilibrium relationship. This suggests that 52% of any deviation from the long-run equilibrium is corrected annually. The moderate adjustment speed reflects the resilience of Singapore's innovation ecosystem and its capacity to absorb shocks while maintaining innovation performance. And in the short term, changes in R&D spending, government grants, and venture capital all exert positive and significant impacts on patent outputs, although these effects are less pronounced than in the long run. This finding highlights the delayed nature of innovation responses, emphasizing that the full impact of R&D investments and supportive funding materializes gradually over time.

Fifth: Diagnostic tests: Using residual tests to ensure the model is free from autocorrelation problems (LM test), variance instability tests (ARCH test), and normality (Jarque-Bera test).

Table 7 summarizes the diagnostic statistics used to verify model assumptions and confirm the adequacy of the regression analysis. The tests include checks for multicollinearity (Variance Inflation Factor), heteroscedasticity (Breusch-Pagan/Cook-Weisberg test), autocorrelation (Durbin-Watson statistic), and model specification (Ramsey RESET test).

Table (7): The Diagnostic Tests

Tests	(p-value)	results
(LM Test) Autocorrelation	0.28	No autocorrelation
(ARCH Test) Heteroscedasticity	0.41	Homoscedasticity
(Jarque-Bera) Natural distribution	0.63	Residuals naturally distributed
(Ramsey RESET) Correct specification	0.19	functional form misspecification**.**

Statistically significant results are indicated, providing evidence of the model's reliability for inference.

Discussion of Key Findings

The findings of this study yield several important insights that are consistent with, and extend, prior research.

Strong Relationship Between Digital Transformation and Innovation:

The results demonstrate that investments in digital transformation—particularly in research, development, and infrastructure—are significant drivers of innovation in emerging institutions. Singapore's RIE2030 plan, which allocates S$6.4 billion (17% of its budget) to research and infrastructure, supplemented by an additional S$1 billion in R&D infrastructure in 2025, exemplifies this strategic commitment. The estimated innovation elasticity of 0.78 indicates a highly efficient conversion of digital inputs into innovative outputs. These findings corroborate prior studies, including Park et al. (2025) and Marin et al. (2023), which emphasize that digitalization enhances the integration of remote and multidisciplinary knowledge, enabling startups to combine scientific expertise with novel technological insights. Similarly, Bigliardi et al. (2025) highlight the critical role of Fourth Industrial Revolution technologies in fostering startup growth and competitiveness.

The Vital Role of Government Policies:

The RIE2025 dummy variable (0.28) confirms that structured government programs substantially promote innovation. This is consistent with extensive evidence demonstrating that government subsidies alleviate financing constraints and enhance patent output (Howell, 2017; Feridrico et al., 2014; Howell & Brown, 2020; Lerner, 2018–2019; Wallsten, 2018; Howell, 2020; Azoulay et al., 2019; Xia et al., 2023; Czarnitzki & Cindy, 2020; David et al., 2020; Bronzini & Lachina, 2014; Liu, 2025). Singapore's AI Trailblazers initiative further illustrates this effect, supporting firms such as Visa, DP Architects, and Ocean Network Express in developing innovative AI solutions (Singapore Economic Development Board, 2025).

Significance of Venture Capital:

Venture capital plays a complementary role to government funding, as evidenced by a long-term coefficient of 0.42. This finding supports the signaling hypothesis posited by Chen (2025), whereby patents serve as indicators to attract investment even in the absence of immediate revenue generation. The result aligns with observed patterns in Singapore, where established startups regularly secure over USD 1 billion in annual investments (Chen, 2025), demonstrating the maturation and efficacy of theventure capital ecosystem.

Existence of Delayed Effects:

The impact of R&D spending manifests over multiple years rather than immediately, highlighting the temporal dimension of innovation processes. This aligns with Zhou and Liu (2025), who emphasize that the pace of R&D adjustments affects innovation efficiency. These findings underscore the importance of evaluating innovation policies over the medium to long term, rather than relying exclusively on short-term outcomes.

Singapore's Ascendancy in Global Innovation:

Singapore's rise to fifth place in the Global Innovation Index 2025 reflects its strengths across sub-indices such as government efficiency and advanced technology exports. Strategic investments, including the USD 37 billion allocated under RIE2030, reinforce the country's competitive advantage. This achievement illustrates the effectiveness of Singapore's integrated innovation ecosystem, which combines government funding, private venture.

6. Conclusions and Recommendations

6.1. Conclusions

- **Digital Transformation and Innovation:**
  Singaporean startups exhibit a strong positive relationship between digital transformation—measured through investments in digital R&D and infrastructure—and innovation, as reflected in patent filings. This finding aligns with prior research emphasizing the role of digitalization in fostering innovation (Park, H. D., et al., 2025; Bigliardi, B. et al., 2025).
- **Role of Government Policies:**
  Regulatory initiatives, such as the RIE plans, play a pivotal role in driving innovation.

The RIE2025 plan, for instance, contributed to a 28% increase in patent registrations, supporting existing evidence on the importance of government assistance in alleviating funding constraints (Zhou, X. M., & Liu, B., 2025). Programs like AI Trailblazers further illustrate the effectiveness of national innovation initiatives (Singapore Economic Development Board, 2025).

- **Temporal Dynamics of Innovation:**
  The transformation of innovation inputs into outputs typically spans one to three years, highlighting the need for strategic long-term planning rather than focusing exclusively on short-term outcomes (Zhou, X. M.,
- **Integrated Innovation Ecosystem:**
  Singapore's innovation ecosystem represents an integrated model that combines government funding, private venture capital, partnerships with global companies, and advanced infrastructure. The effectiveness of this model is supported by both quantitative results and qualitative evidence from successful initiatives such as AXS (Amazon Web Services, 2025) and AI Trailblazers (Singapore Economic Development Board, 2025).
- **Complementarity of Innovation Measures:**
  While patents are key indicators of innovation due to their strong correlation with independent variables, they should be complemented by other metrics, including service and business model innovations, consistent with prior research (Rassenfosse, G., 2024; Chen, V. X., 2025; Zhang, Y., 2018).

6.2. Recommendations

For Policy Makers in Singapore:

- **Link grants to IP registration:** Government grants should be tied to intellectual property registration, incorporating lessons from international experiences regarding stable funding and well-designed policies (Zhou, X. M., & Liu, B., 2025; Léger, Andréanne, 2007).
- **Sustain RIE2030 investments:** Maintain expenditure at 1% of GDP, focusing on high-potential sectors such as artificial intelligence and semiconductors, and enhance public-private collaboration in line with AI Trailblazers objectives (Singapore Economic Development Board, 2025).
- **Develop comprehensive innovation metrics:** Expand beyond patents to include service and business model innovation indicators (Rassenfosse, 2024; Chen, 2025; Zhang, 2018).
- **Stabilize innovation funding:** Ensure consistent R&D funding to avoid disruptions that could compromise innovation efficiency (Zhou, X. M., & Liu, B., 2025).

For Startups:

- **Leverage support programs:** Utilize initiatives such as AI Trailblazers and AWS programs to accelerate innovation and international expansion.
- **Develop integrated IP strategies:** Secure patents early to protect innovations and signal credibility to investors (Chen, V. X., 2025).

- **Strengthen academia-industry partnerships:** Collaborate with universities and research centers, including the National University of Singapore and A*STAR, to convert research into market-ready solutions (Park, H. D., 2025).
- **Diversify funding sources:** Combine government grants with venture capital to maintain funding stability and reduce reliance on any single source (Zhou, X. M., & Liu, B., 2025).

For Other Countries and Global Stakeholders:

- **Learn from Singapore's model:** Develop integrated innovation ecosystems that combine public and private funding, supported by robust digital infrastructure.
- **Foster strategic partnerships:** Emulate Singapore's alliances with global technology leaders, such as Google Cloud and AWS, to accelerate innovation and adoption of advanced digital solutions (Singapore Economic Development Board, 2025; Amazon Web Services, 2025).
- **Invest in knowledge digitization:** Establish platforms for accessible scientific knowledge and patent information to facilitate collaboration and reduce geographic barriers (Park, H. D., 2025).
- **Design integrated support policies:** Align government subsidies with venture capital incentives to ensure stable, efficient capital allocation (Zhou, X. M., & Liu, B., 2025).

6.3 Study Limitations and Future Research Directions

Limitations:

The study's sample period of 11 years, constrained by data availability, may introduce biases and limit the precision of econometric estimates.

Reliance on quantitative metrics such as patent counts may overlook qualitative aspects of innovation, despite efforts to incorporate multiple indicators.

Disentangling the effects of digital transformation from other macroeconomic variables remains challenging, even with policy dummy variables.

Patent counts do not account for differences in intrinsic value or quality, which may introduce measurement errors and affect results.

Future Research Directions:

Conduct comparative studies between Singapore and other Asian countries, such as South Korea and China, to explore policy and outcome differences.

Utilize micro-level data at the individual company level to better capture innovation dynamics and control for firm-specific characteristics such as size, sector, and funding stage.

Investigate the long-term sustainability of startups in relation to digital transformation and examine whether patents reliably translate into revenue generation.

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