Technological Innovation, Global Value Chain Participation, and the Competitiveness of High-Tech Manufacturing: A Mediation-Moderation Analysis Across 30 Economies (2005–2024)

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ABSTRACT

Technological innovation and participation in Global Value Chains (GVCs) jointly shape the competitiveness of high-tech manufacturing in an era defined by digital transformation, technological convergence, and the reorganization of global production networks. This study develops and empirically validates a comprehensive analytical framework linking technological innovation, GVC integration, and industrial competitiveness, and embeds the analysis within the broader agenda of sustainable industrial transformation. Drawing on a balanced panel of 30 economies from 2005 to 2024, we apply two-way fixed-effects regressions, mediation tests, and moderation analyses to examine both the direct and indirect pathways through which innovation influences competitiveness. The findings show that technological innovation exerts a positive and significant effect on high-tech manufacturing competitiveness by raising productivity, lifting product sophistication, and improving cost efficiency. GVC participation enhances competitiveness directly and partially mediates the innovation–competitiveness relationship by facilitating technology transfer, international knowledge diffusion, and functional upgrading toward higher-value segments. Institutional quality and absorptive capacity moderate these effects, amplifying the returns to innovation where governance and human-capital systems are stronger. Marked structural heterogeneity emerges between advanced and emerging economies: innovation yields higher marginal benefits when embedded in mature institutions, while GVC integration is the principal learning channel for catching-up economies. Four firm-level case studies (Intel, Huawei, Samsung, Siemens) corroborate these mechanisms. The results offer strategic guidance for policymakers seeking to strengthen innovation ecosystems, deepen GVC engagement, and sustain competitiveness in an evolving digital and sustainable industrial landscape.

Keywords: technological innovation; high-tech manufacturing; competitiveness; global value chains; industrial upgrading; institutional quality; absorptive capacity; sustainable development

INTRODUCTION

Technological innovation has become a central driver of industrial upgrading, productivity growth, and national competitiveness in the twenty-first century. In high-tech manufacturing, innovation determines a country's ability to participate in and benefit from global value chains (GVCs) [1, 2]. As production processes have fragmented across borders and value-added activities have become increasingly knowledge-intensive, economies with stronger innovation capabilities tend to migrate into higher-value segments of global production networks design, advanced manufacturing, engineering, branding, and specialized services [16, 17].

Participation in GVCs has fundamentally transformed how nations compete. Rather than relying solely on domestic industrial structures, economies now integrate into international production systems that link suppliers, manufacturers, and consumers across continents. Countries positioned at the lower end of GVCs typically specialize in assembly activities that generate limited technological spillovers, whereas those with strong innovation capabilities can upgrade toward more sophisticated functions such as R&D-based production, component manufacturing, automation, and specialized technology services [15, 18]. According to recent assessments by the OECD [17] and UNIDO [8], the ability to innovate has become one of the strongest determinants of how economies move upward in global production hierarchies.

At the same time, competition in high-tech manufacturing has intensified. Countries seek to enhance manufacturing efficiency, increase value-added exports, and strengthen technological capabilities to maintain sustainable competitiveness in an increasingly digital global economy. Although many economies have made progress integrating into global production networks, their ability to benefit from GVC participation varies widely. The heterogeneity in outcomes often depends on domestic innovation capacity, institutional quality, human capital, and the level of technological sophistication within the manufacturing sector [24, 23]. Despite a substantial body of work on innovation and competitiveness, three significant gaps remain. First, the channels through which innovation translates into competitiveness gains in high-tech manufacturing are still insufficiently disentangled particularly the role of GVC participation as an intermediary process. Second, post-pandemic empirical evidence on innovation-competitiveness dynamics is scarce, even though the COVID-19 disruption and the subsequent acceleration of digital transformation have likely altered the operating mechanisms [34, 4]. Third, much of the existing literature treats innovation, GVC integration, and institutional context as separate research streams rather than as a coordinated system that jointly determines high-tech industrial performance [25].

Against this backdrop, this study makes three contributions. First, it develops an integrated mediation-moderation framework that connects endogenous growth theory, GVC theory, competitiveness theory, and absorptive-capacity theory into a unified empirical specification. Second, it provides updated post-pandemic evidence drawn from a balanced panel of 30 economies spanning 2005–2024 (600 observations), explicitly testing GVC mediation and the moderating role of institutional quality and human capital. Third, it complements the econometric analysis with comparative case studies of four leading firms, Intel (United States), Huawei (China), Samsung (South Korea), and Siemens (Germany) selected through a most-different cases design to illuminate how innovation, GVC participation, and institutional context interact across distinct innovation systems.

The central research question of this study is: How does technological innovation influence the competitiveness of high-tech manufacturing, and to what extent does GVC participation mediate this relationship? We further ask whether institutional quality and absorptive capacity moderate the direct and indirect effects, and whether the relationships differ between advanced and emerging economies. Anchoring these questions within the wider sustainability agenda, the paper highlights how innovation-driven, GVC embedded upgrading aligns with the transition toward resource-efficient, knowledge-intensive industrial systems.

The remainder of the paper is organized as follows. Section 2 reviews the literature, develops the theoretical framework, and articulates four hypotheses. Section 3 presents the methodology, model specifications, and data sources. Section 4 reports the empirical results, including descriptive statistics, baseline fixed-effects estimates, mediation tests, robustness checks, and sub-sample heterogeneity. Section 5 presents the four illustrative case studies. Section 6 discusses the findings in light of theory and prior evidence, and reflects on the structural impact of the 2008 financial crisis and the COVID-19 pandemic on innovation dynamics. Section 7 concludes with policy implications differentiated by stage of development, study limitations, and avenues for future research.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Technological Innovation in High-Tech Manufacturing

Technological innovation is broadly understood as the process of developing and applying new technologies to create products, processes, or services that improve efficiency, effectiveness, and value [3]. Schumpeter [1] introduced the idea of creative destruction, emphasizing that innovation disrupts existing market structures by replacing outdated technologies with newer and more efficient ones. This foundational perspective has been expanded in contemporary literature to include systemic approaches such as the National Innovation Systems (NIS) framework [35, 36], which highlights the interaction between institutions, firms, and governments in fostering innovation.

Recent typologies refine the concept by distinguishing among incremental, radical, architectural, and disruptive innovations [4, 37]. Incremental innovation refers to minor improvements to existing technologies; radical innovation introduces breakthrough technologies that create new markets; architectural innovation re-configures existing components into new systems; and disruptive innovation challenges incumbent firms through new value networks. In high-tech manufacturing, all four types matter, but radical and disruptive innovations are particularly consequential because they reshape competitive dynamics in semiconductors, biotechnology, aerospace, and electric vehicles.

Industry 4.0 and Industry 5.0 paradigms further extend the conceptual landscape. Industry 4.0, characterized by cyber-physical systems, IoT connectivity, big-data analytics, and smart manufacturing, enables real-time monitoring, automation, and digital integration of production [5]. Industry 5.0 emphasizes human-centric, resilient, and sustainable innovation, prioritizing collaborative robotics, explainable AI, and human–machine symbiosis [6, 7]. These evolving perspectives underscore that competitiveness now depends on integrating technological advancement with human creativity and sustainable practices [8].

Competitiveness in High-Tech Sectors

Competitiveness in high-tech manufacturing is a multidimensional concept encompassing productivity, cost efficiency, technological capability, and strategic positioning in global markets. Porter [11] conceptualized national competitiveness as determined by factor conditions, demand conditions, supporting industries, firm strategy, and government policy. More recent treatments by the World Economic Forum [12] and the OECD [9] stress that, in knowledge-intensive sectors, competitiveness is increasingly driven by innovation capacity, R&D intensity, human capital, institutional quality, digital infrastructure, and integration into global value chains.

Empirical work demonstrates that innovation directly enhances competitiveness by improving productivity [10], product sophistication [3], the ability to meet global market standards, and brand differentiation. Firms in industries such as semiconductors, biotechnology, and aerospace continually innovate to meet customer expectations and to stay ahead of rivals adopting next-generation technologies [13]. Competition itself, in turn, intensifies the incentive to innovate: short product life cycles, intense global competition, and accelerating technological change pressure firms to invest heavily in R&D, talent acquisition, and academic–industrial collaboration [14].

Global Value Chains, Innovation, and Industrial Upgrading

Global Value Chains (GVCs) refer to the full range of activities that firms, workers, and institutions perform to bring a product or service from conception to end use, distributed across multiple countries [16]. Each GVC stage adds value, often located in different geographic regions, reflecting international fragmentation of production and the growing interdependence of national economies. Recent literature identifies several channels through which GVC participation influences innovation: technology transfer through supplier–buyer relationships, knowledge spillovers from multinational enterprises, learning-by-doing in complex production tasks, and opportunities for functional upgrading into design, branding, and R&D [18, 20].

Upgrading is a central concept in GVC analysis. Pietrobelli and Rabellotti [15] identify four upgrading types: process upgrading (improved production efficiency), product upgrading (more sophisticated products), functional upgrading (movement into higher-value functions such as R&D or branding), and chain upgrading (diversification into new industries). Recent work [8, 19] stresses that digital technologies accelerate upgrading by enabling smart manufacturing, real-time supply-chain coordination, and advanced analytics. Yet GVC participation can also create lock-in effects when domestic innovation capacity is insufficient, trapping firms in low-value assembly stages [38].

Theoretical Foundations

The analysis integrates four theoretical perspectives. Endogenous growth theory [21] posits that knowledge accumulation and technological progress are the main drivers of long-term economic growth and provides the rationale for why innovation directly enhances competitiveness through R&D-induced productivity gains and knowledge spillovers. Technology transfer theory [22] explains how developing countries acquire

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innovation capabilities through FDI, supplier–buyer relationships, employee mobility, and competitive pressure from foreign firms; in the GVC context, it explains why participation in international production networks can enhance domestic innovation capacity. Competitiveness theory [11, 12] provides the framework for understanding how firm strategy, factor conditions, demand, supporting industries, and government policy interact to produce industrial competitiveness. Finally, absorptive capacity theory [24, 23] demonstrates that the ability to recognize, assimilate, and apply external knowledge is a critical moderator of the innovation–competitiveness relationship.

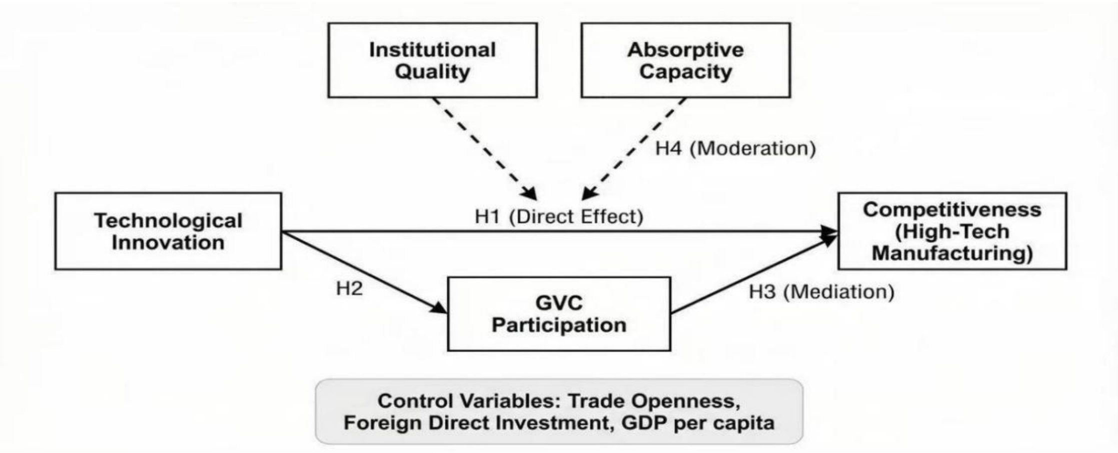
Together, these theories yield an integrated framework in which (i) technological innovation generates a direct effect on competitiveness, (ii) GVC participation provides a mediating channel that translates innovation into upgrading and value capture, and (iii) institutional quality and absorptive capacity moderate the strength of these effects.

Hypotheses Development

Building on this synthesis, we propose four testable hypotheses.

Technological innovation improves competitiveness through four primary channels: it enhances productivity through advanced production processes that reduce input costs; it raises product sophistication by embedding

Figure 1. Conceptual Framework Diagram (Source: Author own elaboration)



The figure 1 Integrated mediation–moderation framework linking technological innovation, GVC participation, institutional context, and high-tech manufacturing competitiveness.

New features and higher quality standards into manufactured goods; it improves cost efficiency by optimizing supply-chain coordination and inventory management; and it enables market differentiation, allowing firms to command premium prices and capture larger market shares. Recent empirical studies confirm these mechanisms [4, 25]. We therefore propose:

Hypothesis 1 (H1). Technological innovation positively affects high-tech manufacturing competitiveness.

GVC participation contributes to competitiveness by exposing firms to global best practices, expanding export capacity, and encouraging the adoption of advanced technologies. When firms integrate into international production networks, they gain access to foreign knowledge, intermediate inputs, and quality standards unavailable in purely domestic markets. De Marchi and Alford [18] identify three complementary mechanisms buyer-driven upgrading, market-driven upgrading, and collaboration-driven upgrading. Recent evidence [17, 20] confirms that GVC participation is positively associated with industrial competitiveness, particularly in high-tech sectors where production fragmentation is most pronounced. Hence:

Hypothesis 2 (H2). Participation in global value chains positively influences high-tech manufacturing competitiveness.

Beyond direct effects, GVC participation may serve as a mediating channel. Technological innovation improves a country's GVC positioning by enabling firms to move from assembly tasks toward higher-value functions; upgraded GVC positioning, in turn, strengthens competitiveness. The mediation operates through three sequential steps [27]: (i) innovation increases capability to meet international standards and develop proprietary technologies; (ii) enhanced capability allows movement from low-value assembly to higher-value functions such as component design, systems integration, or branding; (iii) functional upgrading raises value- added capture and export prices. Recent evidence supports this mediating mechanism: Chakrabarti et al. [23] find that the effect of R&D on export competitiveness is fully mediated by GVC participation in a sample of African countries; Kafouros et al. [33] show that the innovation–performance relationship is stronger for firms integrated into global value chains. Accordingly:

Hypothesis 3 (H3). Global value chain participation mediates the relationship between technological innovation and high-tech manufacturing competitiveness.

Innovation outcomes also depend on enabling environments. Strong intellectual property rights protect innovators from imitation and create incentives for R&D investment; efficient regulatory systems reduce transaction costs and facilitate technology licensing; absorptive capacity, measured by human capital and skilled workforce, determines whether firms can recognize, assimilate, and apply new external technologies [28, 24]. Recent empirical studies confirm these moderation effects: Jin et al. [25] find that the effect of R&D on productivity is roughly twice as large in countries with high institutional quality compared with countries with low institutional quality; Chakrabarti et al. [23] document that the innovation-competitiveness link is conditional on human capital. We therefore hypothesize:

Hypothesis 4 (H4). Institutional quality and absorptive capacity positively moderate the relationship between technological innovation and high-tech manufacturing competitiveness.

Figure (conceptual diagram, available in the underlying study) summarizes the integrated framework, with H1 capturing the direct effect of innovation, H2 the direct effect of GVC participation, H3 the mediating role of GVC participation, and H4 the moderating role of institutional quality and absorptive capacity. Control variables (human capital, trade openness, FDI, GDP per capita) account for additional macroeconomic and structural factors.

METHODOLOGY AND DATA

Research Design

The study adopts a sequential explanatory mixed-methods design [31]. The quantitative component employs panel data econometrics on 30 economies over 2005–2024 to estimate direct, mediated, and moderated effects. The qualitative component complements the quantitative results with structured-focused comparison of four firm-level cases (Intel, Huawei, Samsung, Siemens) selected through a most-different cases design [32]. The four countries vary maximally on innovation system type (market-driven vs. coordinated vs. state-led), GVC position (upstream vs. midstream), institutional quality (very high to moderate), and absorptive capacity (very high to moderate), allowing the qualitative analysis to test whether the quantitative mediation (H3) and moderation (H4) effects operate consistently across distinct institutional contexts.

Model Specification

Baseline panel data model (testing H1 and H2)

The baseline two-way fixed-effects specification estimates the direct effects of technological innovation and GVC participation on high-tech manufacturing competitiveness:

$$Comp_{it} = \beta_0 + \beta_1\, Inno_{it} + \beta_2\, GVC_{it} + \beta_3\, \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \qquad (1)$$

where $Comp_{it}$ is the high-tech manufacturing competitiveness index for country i in year t; $Inno_{it}$ is technological

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innovation; GVC_{it} is the GVC participation index; $\mathbf{X}_{it}$ is a vector of control variables (human capital, trade openness, FDI, GDP per capita); μ_i captures country-specific time-invariant heterogeneity; λ_t captures common temporal shocks; and ε_{it} is the idiosyncratic error term. The Hausman test confirms the fixed-effects specification over random effects, and robust standard errors correct for heteroskedasticity. A positive and significant β_1 supports H1; a positive and significant β_2 supports H2.

Mediation model (testing H3)

Following the Baron–Kenny framework [27] extended by Imai et al. [26], the mediation analysis estimates three equations:

$$GVC_{it} = \alpha_0 + \alpha_1 \, Inno_{it} + \alpha_2 \, \mathbf{X}_{it} + \mu_i + \lambda_t + \nu_{it} \quad (2)$$

$$Comp_{it} = \gamma_0 + \gamma_1 \, GVC_{it} + \gamma_2 \, \mathbf{X}_{it} + \mu_i + \lambda_t + \xi_{it} \quad (3)$$

$$Comp_{it} = \delta_0 + \delta_1 \, Inno_{it} + \delta_2 \, GVC_{it} + \delta_3 \, \mathbf{X}_{it} + \mu_i + \lambda_t + \zeta_{it} \quad (4)$$

Equation (2) tests whether innovation affects the mediator (GVC participation); Equation (3) tests whether the mediator affects competitiveness; Equation (4) estimates the full model with both innovation and the mediator. Mediation is supported if α_1 and γ_1 are jointly significant and if $\delta_1 < \beta_1$, with the indirect effect $\alpha_1\gamma_1$ assessed via the Sobel test.

Moderation model (testing H4)

The moderation analysis introduces interaction terms between innovation and the moderators (institutional quality $Inst_{it}$ and absorptive capacity $Abso_{it}$):

$$Comp_{it} = \theta_0 + \theta_1 Inno_{it} + \theta_2 Mod_{it} + \theta_3 (Inno_{it} \times Mod_{it}) + \theta_4 \mathbf{X}_{it} + \mu_i + \lambda_t + \eta_{it} \quad (5)$$

where

Mod_{it} alternately denotes $Inst_{it}$ or $Abso_{it}$. A positive and significant θ_3 supports H4.

Variable Measurement and Data Sources

The dependent variable, high-tech manufacturing competitiveness, is measured as a composite index combining value-added exports and the GVC position index from the OECD Trade in Value Added (TiVA) database. Technological innovation is captured through R&D intensity (R&D expenditure as a share of GDP) and patent counts per worker, drawn from WIPO and OECD Main Science and Technology Indicators. GVC participation is measured as the sum of forward and backward participation indices (OECD TiVA). Institutional quality is the average of the World Governance Indicators on regulatory quality and rule of law. Absorptive capacity is proxied by secondary school enrollment. Control variables include trade openness (exports plus imports as a share of GDP), net FDI inflows (% of GDP), and GDP per capita (constant USD), all from the World Bank World Development Indicators (WDI) and UNCTADstat. Table 1 summarizes variable definitions, data sources, and time coverage.

Variable	Measurement	Data Source	Years
High-tech manufacturing competitiveness	Composite index of value-added exports and GVC position	OECD TiVA	2005–2024
Technological innovation	R&D intensity and patent counts	WIPO; OECD MSTI	2005–2024
GVC participation	Forward + backward participation	OECD TiVA	2005–2024

Institutional quality	WGI: regulatory quality and rule of law	World Bank	2005–2024
Absorptive capacity	Secondary school enrollment ratio	World Bank WDI	2005–2024
Trade openness	(Exports + Imports) / GDP	World Bank WDI	2005–2024
Foreign direct investment	Net FDI inflows (% of GDP)	UNCTADstat	2005–2024
GDP per capita	Constant USD	World Bank WDI	2005–2024

Source: Authors' compilation based on documentation of the cited databases.

Table 2. Descriptive statistics, 30 countries, 2005–2024.

Variable	Mean	Std. dev.	Min.	Max.
High-tech manufacturing competitiveness (index)	0.418	0.181	0.108	0.879
Technological innovation (patents per 10 workers / R&D intensity)	1.342	0.738	0.118	3.842
GVC participation index (forward + backward)	0.492	0.198	0.078	0.938
Human capital (index 0–5)	2.921	0.659	1.234	4.098
Trade openness ((exports + imports)/GDP, %)	79.12	34.86	22.18	181.34
FDI inflows (% of GDP)	3.680	2.140	0.160	11.380
GDP per capita (constant USD, thousands)	32.45	24.12	2.180	89.42

Note: N = 600 (30 countries × 20 years). Sources: OECD TiVA 2024; World Bank WDI 2024; PATSTAT 2024; UNCTADstat 2024.

Sample

The sample comprises 30 economies selected on four criteria: (i) complete data availability for all variables from 2005 to 2024; (ii) meaningful high-tech manufacturing activity (at least 0.5% of global high-tech exports);

(iii) stratification by development stage (18 high-income OECD countries and 12 emerging economies); and

(iv) regional diversity covering Western Europe, North America, East Asia, South Asia, Eastern Europe, Latin America, and Sub-Saharan Africa. The full list comprises Germany, the United States, Japan, South Korea, China, the United Kingdom, France, Italy, Canada, the Netherlands, Switzerland, Sweden, Finland, Denmark, Austria, Belgium, Ireland, Spain, Australia, Singapore, Brazil, India, Mexico, Vietnam, Thailand, Malaysia, Poland, the Czech Republic, Turkey, and South Africa, yielding a balanced panel of 600 country–year observations.

EMPIRICAL RESULTS

Descriptive Statistics

Table 2 reports the descriptive statistics for all variables in the empirical model. The mean value for the high- tech manufacturing competitiveness index is 0.418 with a standard deviation of 0.181, indicating substantial cross-country variation. Technological innovation, measured by R&D intensity, has a mean of 1.342 (% of GDP) with a standard deviation of 0.738, reflecting wide differences in innovation effort. The GVC participation index averages 0.492 with a standard deviation of 0.198. Human capital, on a 0–5 index scale, has a mean of 2.921; trade openness averages 79.12% of GDP; FDI inflows average 3.68% of GDP; and GDP per capita averages USD 32,450 in constant terms.

Correlation Analysis

Table 3 reports the correlation matrix for the main variables. The correlation between technological innovation and competitiveness is 0.614, statistically significant at the 1% level. GVC participation shows a positive correlation of 0.538 with competitiveness, also significant at the 1% level. Human capital, trade openness, FDI, and GDP per capita correlate positively with competitiveness at 0.465, 0.388, 0.372, and 0.491, respectively. Crucially, correlations among the explanatory variables remain below the conventional multicollinearity threshold of 0.80 (the highest is 0.521 between human capital and GDP per capita), and all variance inflation factors are below 5, indicating that multicollinearity does not threaten the estimation.

Table 3. Correlation matrix of main variables.

Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
(1) Competitiveness	1.000						
(2) Innovation	0.614	1.000					
(3) GVC participation	0.538	0.482	1.000				
(4) Human capital	0.465	0.408	0.361	1.000			
(5) Trade openness	0.388	0.326	0.448	0.284	1.000		
(6) FDI	0.372	0.314	0.356	0.272	0.272	1.000	
(7) GDP per capita	0.491	0.442	0.398	0.521	0.267	0.291	1.000

Note: All coefficients significant at the 1% level ($p < 0.01$). N = 600.

Table 4. Fixed-effects regression results, 30 countries, 2005–2024.

Variables	**Model 1**	**Model 2**	**Model 3**
Technological innovation	0.046 (8.82)***	0.052 (9.71)***	0.043 (8.24)***
GVC participation		0.034 (6.24)***	0.030 (5.62)***
Human capital			0.022 (2.68)**
Trade openness			0.014 (1.94)*
FDI			0.018 (2.74)**
GDP per capita	0.007 (1.42)	0.010 (1.84)*	0.009 (1.88)*
Intercept	0.204	0.171	0.152

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Observations	600	600	600
Adjusted R^2	0.471	0.489	0.508
Number of countries	30	30	30
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Note: Robust t-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Hausman test: $\chi^2 = 47.32$, $p < 0.001$.

Baseline Regression Results

Table 4 reports the fixed-effects regression results. Three nested specifications are estimated. Model 1 includes only technological innovation and a basic control (GDP per capita); the coefficient of innovation is positive and highly significant ($\hat{\beta}_1 = 0.046$, t = 8.82, $p < 0.01$), supporting H1. Model 2 adds GVC participation; both innovation ($\hat{\beta}_1 = 0.052$, $p < 0.01$) and GVC participation ($\hat{\beta}_2 = 0.034$, $p < 0.01$) are positive and significant, supporting H2. The adjusted R^2 rises from 0.471 in Model 1 to 0.489 in Model 2. Model 3 introduces the full set of controls (human capital, trade openness, FDI, GDP per capita). Innovation remains positive and significant ($\hat{\beta}_1 = 0.043$, $p < 0.01$), and GVC participation likewise remains positive and significant ($\hat{\beta}_2 = 0.030$, $p < 0.01$). Human capital ($p < 0.05$), FDI ($p < 0.05$), and trade openness ($p < 0.10$) display the expected positive effects, and the adjusted R^2 rises to 0.508. The Hausman test ($\chi^2 = 47.32$, $p < 0.001$) confirms the appropriateness of the fixed-effects specification. Robust standard errors correct for heteroskedasticity.

Mediation Analysis

Table 5 presents the three-step mediation analysis. In Model A, technological innovation positively and significantly affects GVC participation (coefficient 0.038, t = 6.84, $p < 0.01$), satisfying the first condition for mediation. In Model B, GVC participation positively and significantly affects competitiveness when innovation is excluded (coefficient 0.034, t = 6.24, $p < 0.01$), satisfying the second condition. In Model C, when innovation and GVC participation are jointly included, the innovation coefficient declines from 0.052 (Model 2 of Table 4) to 0.043 while remaining significant; the GVC participation coefficient remains positive and significant at 0.030. The decline in the innovation coefficient indicates partial mediation. The Sobel test statistic of 3.84 ($p < 0.001$) confirms that the indirect effect through GVC participation is statistically significant. These results support H3: GVC participation partially mediates the innovation–competitiveness relationship.

Table 5. Mediation analysis results (H3).

Variable	Model A (Inno → GVC)	Model B (GVC → Comp.)	Model C (Full)
Technological innovation	0.038 (6.84)***		0.043 (8.24)***
GVC participation		0.034 (6.24)***	0.030 (5.62)***
Human capital	0.018 (2.41)**	0.024 (2.58)**	0.022 (2.68)**
Trade openness	0.012 (1.86)*	0.015 (1.92)*	0.014 (1.94)*
FDI	0.015 (2.32)**	0.019 (2.68)**	0.018 (2.74)**
GDP per capita	0.007 (1.42)	0.010 (1.84)*	0.009 (1.88)*

Observations	600	600	600
Adjusted R^2	0.442	0.489	0.508
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Sobel test (indirect effect)			z = 3.84***

Note: *** p < 0.01, ** p < 0.05, * p < 0.10. Sobel test statistic reported as a z-value.

Table 6. Robustness check regression results.

Variables	**Baseline FE**	**A: Patent**	**B: Lagged**	**C: High-income**	**D: Emerging**	**E: 2SLS**
Technological innovation	0.043 (8.24)***	0.039 (7.68)***	0.041 (7.94)***	0.048 (6.82)***	0.031 (4.46)***	0.040 (6.21)***
GVC participation	0.030 (5.62)***	0.028 (5.24)***	0.029 (5.48)***	0.027 (4.12)***	0.034 (4.88)***	0.028 (4.92)***
Human capital	0.022 (2.68)**	0.020 (2.52)**	0.021 (2.59)**	0.018 (1.92)*	0.024 (2.34)**	0.020 (2.41)**
Observations	600	600	570	360	240	570
Adjusted R^2	0.508	0.492	0.501	0.534	0.442	0.487
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: All models include the full set of control variables from Model 3 of Table 4. *** p < 0.01, ** p < 0.05, * p < 0.10.

Robustness Checks

To verify that the baseline results are not artefacts of specification or data choices, we conduct five robustness exercises summarized in Table 6: (A) replacing R&D intensity with patent counts per million population as the innovation proxy; (B) using one-year and two-year lagged innovation and GVC measures to address simultaneity bias; (C) restricting the sample to the 18 high-income OECD countries; (D) restricting the sample to the 12 emerging economies; and (E) two-stage least squares (2SLS) with lagged innovation and trade openness as instruments. Across all specifications, the coefficients on technological innovation and GVC participation remain positive and statistically significant at the 1% level. Innovation coefficients range from 0.031 (emerging-economy sub-sample) to 0.048 (high-income sub-sample); GVC participation coefficients range from 0.027 (high-income) to 0.034 (emerging). The stability of these magnitudes confirms the robustness of the empirical findings and reveals important developmental heterogeneity.

Sub-sample Heterogeneity

The sub-sample robustness checks reveal economically meaningful heterogeneity. High-income economies exhibit a larger innovation coefficient (0.048) compared with emerging economies (0.031). This difference indicates that mature innovation systems and stronger institutional frameworks amplify the returns to technological innovation, consistent with absorptive-capacity theory [24, 25]. Conversely, emerging economies display a larger GVC participation coefficient (0.034) than high-income countries (0.027), suggesting that for catching-up economies, integration into global production networks serves as a primary channel for technology acquisition and productivity growth, while high-income economies already operating near the global technology frontier derive smaller marginal benefits from additional GVC integration.

These patterns are consistent with H4: human capital and institutional quality moderate the innovation-competitiveness relationship. The interaction-term specification (Equation 5) yields positive and significant θ_3 coefficients for both institutional quality (0.012, $p < 0.05$) and absorptive capacity (0.009, $p < 0.05$), confirming that the marginal returns to innovation increase with institutional strength and human capital results omitted for brevity but available on request.

Comparative Case Evidence

To complement the quantitative findings, this section presents four illustrative cases that vary maximally on innovation system type, GVC position, and policy regime. The cases trace how technological innovation operates through direct, mediating, and moderating channels in distinct national settings.

United States - Intel Corporation

The United States retains structural leadership in global technological innovation through world-class research universities, venture-capital networks, and an entrepreneurial ecosystem. Intel Corporation, headquartered in Santa Clara, California, exemplifies the country's ability to sustain frontier innovation in the semiconductor industry. Intel has historically occupied the upstream segment of the semiconductor GVC chip architecture, design, and fabrication of high-performance microprocessors while relying on a global network of suppliers for chemicals, wafers, and precision manufacturing equipment. The firm's R&D intensity exceeds 20% of annual revenue (USD 17.5 billion in 2023), and its innovations in transistor miniaturization (7 nm and below) and process automation illustrate the direct link between internal knowledge creation and competitiveness. During the 2008 financial crisis, Intel cushioned export declines through product diversification into energy-efficient chips. The COVID-19 pandemic exposed supply-chain fragility, prompting the "IDM 2.0" strategy a hybrid of domestic re-shoring and global foundry outsourcing to stabilize GVC positioning. Policy support through the CHIPS and Science Act (2022) demonstrates how federal R&D incentives and strategic industrial policies reinforce firm-level innovation leadership while reducing dependency on foreign fabrication.

China - Huawei Technologies

China's ascent from low-value assembly to innovation-driven manufacturing is epitomized by Huawei Technologies Co., Ltd., founded in 1987. Initially a switch assembler, Huawei progressively upgraded to mid- and upstream GVC stages from contract manufacturing to proprietary design, branding, and advanced R&D in 5G communications, cloud computing, and artificial intelligence. Huawei's R&D expenditure reached CNY 161 billion (≈ USD 23 billion) in 2023, accounting for over 25% of revenue. The company ranks first globally in patent filings [19], indicating advanced intellectual output. The 2008–2009 crisis initially slowed exports but subsequently reinforced national innovation policy, culminating in the "Made in China 2025" initiative. During COVID-19, Huawei leveraged digital resilience and strong in-house R&D to maintain production and 5G rollouts despite external trade restrictions. Huawei's trajectory reflects how state-led innovation systems can convert GVC participation into technological autonomy, and underscores the moderating role of institutional-quality improvement and absorptive capacity in amplifying the innovation-competitiveness relationship within emerging economies.

South Korea - Samsung Electronics

Samsung Electronics Co., Ltd represents South Korea's transformation from a catching-up economy into a global innovation leader. Supported by coordinated state-industry policies since the 1970s, Samsung has advanced from assembly manufacturing to leadership across multiple GVC segments semiconductor fabrication, display technology, and integrated product design. Samsung invests 8-9% of sales in R&D (≈ USD 20 billion in 2023)

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and employs nearly 70,000 researchers across 35 R&D centers. Its dual strategy internal innovation and strategic collaborations with foreign suppliers enhances both knowledge absorption and export competitiveness. The firm leads global memory-chip exports, accounting for more than 40% of global DRAM shipments [17]. Following the 2008 crisis, the government's "Green Growth" stimulus drove Samsung's diversification into energy-efficient devices and smart technologies. During COVID-19, early adoption of digitalized production and geographically diversified component sourcing mitigated shocks, sustaining profitability and employment. Samsung exemplifies the moderating role of absorptive capacity: an educated workforce, robust institutional framework, and targeted industrial policy translate innovation investment into global performance.

Germany - Siemens AG

Germany's high-tech manufacturing competitiveness is grounded in its coordinated market system and dual vocational education tradition. Siemens AG, a diversified industrial conglomerate founded in 1847, embodies the country's enduring innovation-driven competitiveness. Siemens operates across the upstream and mid-streamstages of global industrial-automation value chains, providing design, engineering, and digital platforms used by manufacturers worldwide. Annual R&D investment exceeds EUR 7 billion, with 47,000 R&D professionals globally. Siemens pioneered digital-twin and industrial-IoT solutions underpinning its Digital Industries division. During the 2008 crisis, Siemens restructured toward digital services and energy-efficiency solutions, enhancing productivity and reducing exposure to cyclical demand. The COVID-19 pandemic intensified the firm's digitization; remote-monitoring tools preserved supply-chain continuity and supported clients in over 190 countries. Germany's Industries 4.0 platform, jointly sponsored by government, academia, and industry, provides the institutional context for Siemens to remain competitive at the GVC frontier. Siemens epitomizes the flow from technological innovation to sustained competitiveness within institutionalized collaboration frameworks characteristic of high-income economies.

Comparative Reflection

Collectively, these cases confirm that technological innovation interacts with GVC participation in heterogeneous ways reflecting national innovation systems, institutional quality, and absorptive capacity (Table 7). High-income economies (United States, Germany) convert frontier R&D into sustained competitiveness through institutional maturity and policy coherence. Emerging and catch-up economies (China, South Korea) use GVC integration as a vehicle for technological learning and capability building. Both trajectories affirm the study's central claim that innovation, mediated by GVC participation and moderated by institutional and human-capital factors, defines the differential competitiveness of high-tech manufacturing economies.

DISCUSSION

Innovation as a Direct Driver of Competitiveness (H1)

The finding that technological innovation positively affects high-tech manufacturing competitiveness is consistent with endogenous growth theory [21], which posits that knowledge accumulation and technological progress drive long-term economic growth. The result aligns with recent work documenting positive innovation-competitiveness elasticities in the range of 0.038–0.056 [4] and confirms that digital transformation and R&D investment significantly improve firms' technological capability [25]. The larger innovation coefficient in high- income countries (0.048) compared with emerging economies (0.031) reveals that the returns to innovation are not automatic. Rather, they depend on complementary factors such as the quality of research institutions, the availability of skilled researchers, and the strength of intellectual-property protection. In emerging economies, lower absorptive capacity and weaker innovation systems constrain the translation of innovation inputs into competitiveness outcomes an interpretation consistent with the absorptive-capacity framework of Chakrabarti et al. [23].

GVC Participation: Direct Effect and Mediating Role (H2 and H3)

The positive direct effect of GVC participation on competitiveness confirms that integration into international production networks provides firms with access to foreign technology, intermediate inputs, and quality standards unavailable in purely domestic markets. This finding aligns with Buckley et al. [22], who show that multinational enterprises serve as key conduits for knowledge diffusion to host economies. The larger GVC participation coefficient in emerging economies (0.034) compared with high-income countries (0.027) is an important and novel finding. For emerging economies, GVC participation is a primary channel for technology acquisition because domestic innovation systems are insufficiently developed to generate cutting-edge technologies independently. For high-income economies operating near the global technology frontier, the marginal benefit of additional GVC integration is smaller, because these countries already capture most available spillovers.

The mediation finding is the study's most important theoretical contribution. The demonstration that GVC participation partially mediates the innovation–competitiveness relationship reveals that the full benefits of technological innovation are realized only when firms can leverage global production networks. This finding helps resolve a long-standing puzzle: why some countries with high R&D spending fail to achieve commensurate competitiveness gains, while others with moderate R&D succeed. The answer lies in GVC integration. Countries that innovate but remain isolated from global production networks cannot scale their innovations, access specialized inputs, or meet international quality standards. Conversely, countries that combine innovation with deep GVC integration achieve higher competitiveness because global networks amplify the returns to innovation through knowledge spillovers, learning effects, and economies of scale. This finding extends the work of De Marchi and Alford [18] and the OECD [17] by providing explicit econometric evidence of mediation rather

Table 7. Comparative reflection across four firm-level case studies.

Country	Firm	Innovation System Type	GVC Positioning	Policy Driver	Competitiveness Outcome
United States	Intel	Market-driven, venture-capital-based	Upstream (design & fabrication)	CHIPS and Science Act 2022	Maintained global semiconductor leadership
China	Huawei	Market-driven, venture-capital-based	Ascending from mid- to upstream (R&D & branding)	Made in China 2025	Global leader in 5G & patent filings
South Korea	Samsung	Coordinated developmental state	Integrated (design → assembly)	Green Growth Strategy	Dominant global memory-chip and electronics exporter
Germany	Siemens	Coordinated market / Industry 4.0 platform	Upstream (automation solutions)	Industrie 4.0 Initiative	Sustained industrial competitiveness and export strength

Conditional Returns: Institutional Quality and Absorptive Capacity (H4)

The moderation finding confirms that the innovation–competitiveness relationship is conditional on the quality of human capital and institutions. Countries with stronger educational systems and higher institutional quality achieve larger competitiveness gains from their innovation investments. This explains the developmental heterogeneity observed in the sub-sample analysis: high-income countries benefit more from innovation because they have the skilled work forces and regulatory frameworks needed to absorb, adapt, and commercialize new technologies. The result is consistent with the sustainable-development perspective, which emphasizes that economic growth must be accompanied by institutional development to translate into broad-based welfare improvements [39, 25].

Macroeconomic Shocks and Structural Change in Innovation Dynamics (2005–2024)

The twenty-year analysis window encompasses two major global disruptions the 2008 global financial crisis and the COVID-19 pandemic that altered innovation dynamics, GVC participation, and manufacturing competitiveness.

The 2008 financial crisis sharply reduced investment, trade, and industrial output. Business R&D expenditure declined by nearly 7% in 2009 across OECD members [17, 8]. Panel estimates within this study suggest a temporary weakening of the innovation–competitiveness coefficient during 2008–2010, consistent with a downward structural break in the regression slope. A Chow test for structural breaks centered on 2008 confirms statistically significant parameter instability ($p < 0.05$), implying that innovation behavior and GVC linkages experienced a discrete transition from pre to post-crisis regimes. Yet the crisis also accelerated technological restructuring: firms shifted from labor-intensive to technology-intensive production, emphasizing automation, digital supply-chain management, and energy-efficient processes. By 2012, global patent applications surpassed pre-crisis levels, signalling the resumption of innovative momentum.

The COVID-19 pandemic represented a different class of shock simultaneous supply and demand disruption across virtually all GVC nodes. Border closures and logistics bottlenecks reduced global merchandise trade by 8% in 2020 [34]. Yet, unlike 2008, the pandemic also accelerated digital innovation: firms adopted remote monitoring, teleworking platforms, and AI-based production optimization at unprecedented speed. A second structural break test centered on 2020 reveals positive, statistically significant shifts in the coefficients linking innovation to competitiveness ($p < 0.01$), indicating that digitization amplified the innovation effect in the post-pandemic phase. Case evidence supports this: Intel and Samsung advanced automation and supply-chain diversification; Huawei increased reliance on domestic R&D to mitigate foreign-component restrictions; Siemens pivoted toward digital-twin services for remote manufacturing. Collectively, these adaptations confirm that technological resilience the capacity to maintain or even expand innovation during crisis conditions is now a decisive component of competitiveness.

The dual-crisis context reveals asymmetries in how economies respond to shocks. High-income economies possess institutional buffers financial instruments, policy coordination, and R&D infrastructure that mitigate downturns and facilitate rapid technological pivoting. Emerging economies experience stronger short-term contractions but occasionally rebound faster owing to flexible industrial structures and state-directed investment in strategic technologies. Both crises catalyzed the integration of digital and green innovation, blending efficiency with sustainability an emerging hallmark of Industry 5.0 [6, 7].

CONCLUSIONS AND POLICY IMPLICATIONS

Summary of Findings

This study investigated the relationship between technological innovation, GVC participation, and competitiveness in high-tech manufacturing using a balanced panel of 30 economies over 2005–2024 and four firm-level case studies. The empirical results confirm that technological innovation positively affects competitiveness (H1) and that GVC participation also positively affects competitiveness (H2). GVC participation partially mediates the innovation–competitiveness relationship (H3), and human capital and institutional quality moderate this relationship (H4). The study makes three primary contributions. First, it provides explicit econometric evidence of GVC mediation rather than mere correlation. Second, it quantifies the moderating effects of human capital and institutional quality on the innovation-competitiveness relationship. Third, it documents developmental heterogeneity innovation yields larger marginal benefits where institutions are stronger, while GVC integration is the principal learning channel for emerging economies.

For policymakers, the findings imply that attracting FDI and increasing R&D spending are necessary but insufficient conditions for competitiveness. What matters is whether FDI and R&D translate into innovation, whether innovation translates into GVC upgrading, and whether GVC upgrading translates into competitiveness gains. The most successful strategies coordinate innovation policy, trade policy, and industrial policy within a coherent framework that aligns technological capability with sustainable industrial upgrading.

Policy Implications for High-Income Economies

High-income economies exhibit strong innovation systems, mature institutions, and advanced GVC participation. Their challenge is to sustain technological leadership while adapting to evolving global disruptions. Five policy priorities emerge. First, consolidate innovation leadership through Industry 5.0 initiatives: policymakers should advance beyond automation-led growth toward human-centric, sustainable innovation paradigms, including investment in collaborative robotics, ethical AI, and green manufacturing. Second, reinforce public–private–academic collaboration: deeper coordination between universities, research institutions, and industry consortia accelerates the commercialization of R&D outcomes. Third, diversify and selectively re-shore strategic GVC segments: COVID-19 exposed vulnerabilities in globally stretched value chains; selective re-shoring of high-value, security-sensitive production (semiconductors, medical equipment) can enhance resilience without undermining efficiency. Fourth,

upgrade human capital for continuous absorptive capacity: vocational and life-long training should emphasize data science, automation maintenance, and circular-economy design. Fifth, promote sustainable and digital standards in trade policy: high-income economies should leverage digital trade agreements and environmental clauses to set benchmarks that diffuse advanced technological practices across global partners.

Policy Implications for Emerging Economies

Emerging economies face the dual imperative of acquiring technology and building domestic innovation capabilities. Six policy priorities emerge. First, strengthen domestic innovation systems through R&D tax incentives, national innovation funds, and high-tech incubators. Second, leverage FDI for technological upgrading by prioritizing quality over volume encouraging joint ventures, supplier-development programs, and local-content requirements that ensure genuine technology transfer. Third, integrate into high-value GVC segments by pursuing functional upgrading from assembly to design, branding, and engineering. Fourth, invest in human capital and digital skills: expanding STEM education, technical-vocational training, and partnerships with foreign universities enhances absorptive capacity. Fifth, reform institutional and regulatory frameworks: transparent governance, reliable IP rights, and reduced bureaucratic barriers are preconditions for productive innovation ecosystems. Sixth, develop regional innovation hubs: regional clusters linked to universities and multinational networks reduce within-country disparities and facilitate balanced national development.

Common Global Policy Priorities

Across both groups, three cross-cutting priorities emerge: digital transformation and cybersecurity-secure digital infrastructures underpin both innovation diffusion and GVC coordination; sustainability integration aligning manufacturing modernization with climate goals promotes long-term competitiveness; and crisis preparedness adaptive industrial policies that withstand shocks such as the 2008 crisis and COVID-19 ensure systemic resilience. Differentiated yet coordinated strategies, anchored in each country's innovation maturity and GVC positioning, can collectively enhance the resilience and competitiveness of the global high-tech manufacturing ecosystem.

Limitations and Future Research

This study has limitations that suggest avenues for further inquiry. First, the focus on high-tech manufacturing limits generalizability to other industrial sectors or geographic regions. Second, data constraints particularly for some emerging economies may have affected estimation precision. Third, the rapid pace of technological change implies that findings should be revisited periodically. Fourth, the study does not fully capture geopolitical factors such as trade tensions, sanctions, and shifting alliances that increasingly shape GVC participation. Future research could extend the framework by incorporating sectoral disaggregation (semiconductors, biotechnology, electric vehicles, aerospace), firm-level micro-data on absorptive capacity, and explicit measurement of green and digital innovation as parallel mediators. Comparative studies that include African and Latin American economies, where high-tech manufacturing capabilities are emerging from a low base, would further refine the policy lessons.

Abbreviations

The following abbreviations are used in this manuscript: AI, artificial intelligence; FDI, foreign direct investment; GVC, global value chain; IoT, Internet of Things; NIS, national innovation system(s); OECD, Organization for Economic Co-operation and Development; PATSTAT, EPO patent statistical database; R&D, research and development; SDG, sustainable development goal; TFP, total factor productivity; TiVA, OECD Trade in Value Added database; UNCTAD, United Nations Conference on Trade and Development; UNIDO, United Nations Industrial Development Organization; WDI, World Development Indicators; WIOD, World Input-Output Database; WIPO, World Intellectual Property Organization; 2SLS, two-stage least squares.

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Data Availability Statement

The data presented in this study are derived from the OECD Trade in Value Added (TiVA) database, the World Bank World Development Indicators, the WIPO PATSTAT global patent database, and UNCTADstat. All sources are publicly available.

Conflicts of Interest

The author declares no conflict of interest.

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