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Industry–University Collaboration and Regional Innovation Performance: Evidence from R&D Zones Using a Quadruple Helix Growth Framework

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Abstract

Amid increasing organizational complexity and uncertainty, this study explores the link between industry–university collaboration and regional economic performance in designated R&D zones. Drawing on the Quadruple Helix growth framework, which conceptualizes innovation as an interaction among firms, universities, government, and civil society, the analysis evaluates whether technology commercialization activities contribute to firm-level revenue growth. Using regional panel data from four Korean R&D zones over the period 2013–2022, the study estimates a fixed-effects regression model incorporating labour inputs, public expenditure, innovation outputs, and collaboration indicators. The results indicate that technology transfer activities and research-based spin-off formation are positively associated with firm revenue. In contrast, aggregate public expenditure and several R&D input measures do not show statistically significant effects. These findings suggest that the economic contribution of public research is most evident when knowledge is actively translated into market-facing activities. The study contributes to regional innovation research by empirically clarifying the conditions under which Quadruple Helix interactions are associated with local economic outcomes.

Keywords: *Research and Development (R&D) zones, Industry–university collaboration, Regional innovation performance, Regional economic performance, Quadruple Helix framework, Technology commercialization*

1. Introduction

Across many advanced economies, regional development outcomes are increasingly shaped by demographic ageing, labour mobility, and the restructuring of local industry. These shifts have renewed interest in innovation-led regional development, particularly in places where traditional sectors face declining competitiveness and where attracting large external

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employers is uncertain. Within this policy and research context, universities and public research organisations are frequently positioned as "anchor" institutions that can support regional capability-building through knowledge production, skills development, and convening functions within innovation ecosystems [1][2].

A central proposition in regional innovation research is that economic outcomes are not driven solely by research investment, but by the effectiveness of linkages that translate knowledge into practice. Collaboration among firms, universities, and public agencies is therefore commonly understood as a mechanism that can strengthen absorptive capacity, accelerate the circulation of ideas, and support commercial application. However, evidence remains mixed regarding which elements of collaboration are most strongly associated with regional economic performance, and whether upstream research inputs (e.g., R&D expenditure and research labour) or downstream commercialisation outputs (e.g., patents, technology transfer, and spin-off activity) provide clearer links to firm-level growth [3].

The Quadruple Helix perspective extends earlier innovation-system approaches by explicitly incorporating civil society and end users alongside industry, academia, and government. This broadened framing has been applied in regional innovation and smart specialisation research to highlight the roles of participation, legitimacy, and demand formation in shaping innovation pathways [4][5][6]. At the same time, empirical work has underscored that “helix” interactions are not automatically productive; the contribution of universities in peripheral or non-metropolitan regions may be constrained by limited industrial capacity, institutional fragmentation, or weak commercial pipelines [1]. Consequently, a key analytical task is to specify which observable activities plausibly operationalize Quadruple Helix interactions and how those activities relate to measurable economic outcomes.

In this study, the focus is placed on technology commercialisation channels—specifically, technology transfer and research-based spin-off formation—as concrete mechanisms through which public research may influence firm performance. Prior empirical evidence suggests that the commercialisation of transferred public technologies can be associated with subsequent business growth. Still, the strength of these relationships depends on contextual conditions and the effectiveness of translating research outputs into market-facing applications [3]. Building on this logic, the present study tests whether collaboration-linked commercialisation indicators are associated with firm revenue within designated R&D zones, after accounting for labour inputs, public expenditure, and innovation-related outputs.

Using regional panel data from four Korean R&D zones over the period 2013–2022, the study estimates an empirical model consistent with a Quadruple Helix growth framing. It evaluates whether commercialisation activities are systematically linked to regional firm performance. The contribution is primarily empirical and clarificatory: rather than assuming that public R&D inputs translate into regional growth, the analysis distinguishes between upstream inputs and downstream commercialisation channels. It assesses which factors show stronger associations with observed economic outcomes in zone-based innovation settings [2][4][7].

The remainder of the paper is organised as follows. Section 2 reviews the literature on collaboration-based regional innovation and outlines the Quadruple Helix growth framing used in this study. Section 3 presents the data and empirical methodology. Section 4 reports the estimation results, and Section 5 discusses implications for research and regional innovation practice.

2. Literature review

2.1. Industry–university collaboration and the commercialization pathway

A central claim in the regional innovation literature is that collaboration between firms and universities can improve regional economic outcomes by strengthening firms' access to knowledge, problem-solving capability, and innovation resources. However, more recent empirical work has cautioned against treating collaboration as uniformly beneficial; observed effects vary with institutional context, partner capabilities, and the extent to which collaboration is oriented toward market-facing outcomes rather than research activity alone [8][9].

Accordingly, a key analytical distinction concerns upstream R&D inputs versus downstream commercialisation outputs. R&D expenditure and research labour are necessary for knowledge creation. Yet, they often exhibit weak or delayed relationships with firm performance because the pathway from research to market is mediated by selection, translation, and adoption processes. In contrast, indicators such as licensing, technology transfer agreements, and research-based spin-off activity reflect more direct knowledge-to-market mechanisms that are expected to relate more closely to observable economic outcomes [10]. Empirical evidence from technology transfer data suggests that the commercialisation of publicly developed technologies can be associated with subsequent business growth. However, the magnitude of the effects depends on adoption conditions and the effectiveness of transfer processes.

In addition to the commercialisation channel, scholarship on university entrepreneurship highlights the role of spin-offs as a structured vehicle for translating research into regional economic activity. Recent syntheses show that spin-off performance is shaped by a combination of organisational capabilities, external partnerships, and the institutional infrastructure that supports entrepreneurial development and scaling [11]. Complementary evidence further indicates that collaboration relationships can facilitate spin-off formation and shape commercial viability by strengthening market understanding and providing routes to external resources [12]. These studies collectively suggest that the regional economic relevance of university engagement is most evident when collaboration yields commercially actionable outputs.

2.2. Quadruple helix perspectives and regional innovation systems

While collaboration studies often focus on bilateral (firm–university) or trilateral (industry–university–government) relationships, Quadruple Helix perspectives broaden the conceptual frame by incorporating civil society and end users. This extension emphasises that innovation is not only supply-driven (knowledge creation) but also shaped by demand formation, legitimacy, and wider participation in innovation processes [13]. Comparative conceptual work has also argued that the Quadruple Helix is particularly relevant where innovation outcomes depend on societal embedding, public value, and inclusive participation rather than on R&D intensity alone.

Empirical studies adopting Quadruple Helix logic frequently operationalize the framework through measurable interaction patterns, actor configurations, and innovation outcomes at the regional level. Research examining Quadruple Helix interactions highlights the role of civil society as more than a passive recipient, suggesting that social capital and participatory dynamics can influence innovation performance and institutional coordination [14]. Related work on regional smart specialisation initiatives has shown that Quadruple Helix

arrangements can shape the effectiveness of place-based innovation strategies by structuring the relationships and resource exchanges among actors [8][9]. From this perspective, "helix" models are best treated as conditional: they provide an organising framework, but the realised economic effects depend on how interaction mechanisms are implemented and whether they enable credible commercial pathways.

2.3. Smart specialization, university research commercialization, and regional outcomes

A further strand of research relevant to this study concerns how place-based policy frameworks influence collaboration and commercialisation. Evidence from smart specialisation research indicates that regional policy can shape university–industry engagement by steering investment priorities, incentivising partnership formation, and influencing the development of commercialization infrastructure, although implementation challenges and institutional fragmentation remain common [15]. Complementary work has examined how smart specialisation intersects with university research commercialisation, including the extent to which regional industrial relatedness and university capability profiles shape commercialisation patterns [16]. Together, these findings reinforce the view that regional economic outcomes are sensitive to both actor capabilities and governance design.

Recent empirical studies continue to test whether collaboration improves measurable firm performance. Firm-level evidence suggests that university–industry collaboration can be associated with productivity improvements through mechanisms such as higher-quality innovation and improved internalisation of knowledge. However, effects vary with context and measurement choices [15]. At the same time, regional policy research highlights that innovation strategies often sit between experimentation and administrative compliance, raising questions about when policy-driven collaboration translates into durable economic outcomes [16]. These perspectives motivate an empirical approach that distinguishes between inputs (e.g., R&D budgets and researchers) and commercialisation outputs (e.g., patents, technology transfer, and spin-offs) when evaluating economic performance in zone-based innovation environments.

2.4. Positioning of the present study

Building on the above literature, the present study adopts a Quadruple Helix–consistent growth framing and focuses empirically on technology commercialisation indicators—technology transfer and research-based spin-offs—as observable mechanisms linking public research activity to firm revenue outcomes. In doing so, the study addresses the empirical gap identified in prior work: the need to evaluate whether regional innovation investments translate into economic performance primarily through commercially actionable outputs rather than solely through upstream inputs [10][11][12]. The analytical model, variables, and hypotheses are developed in the following section.

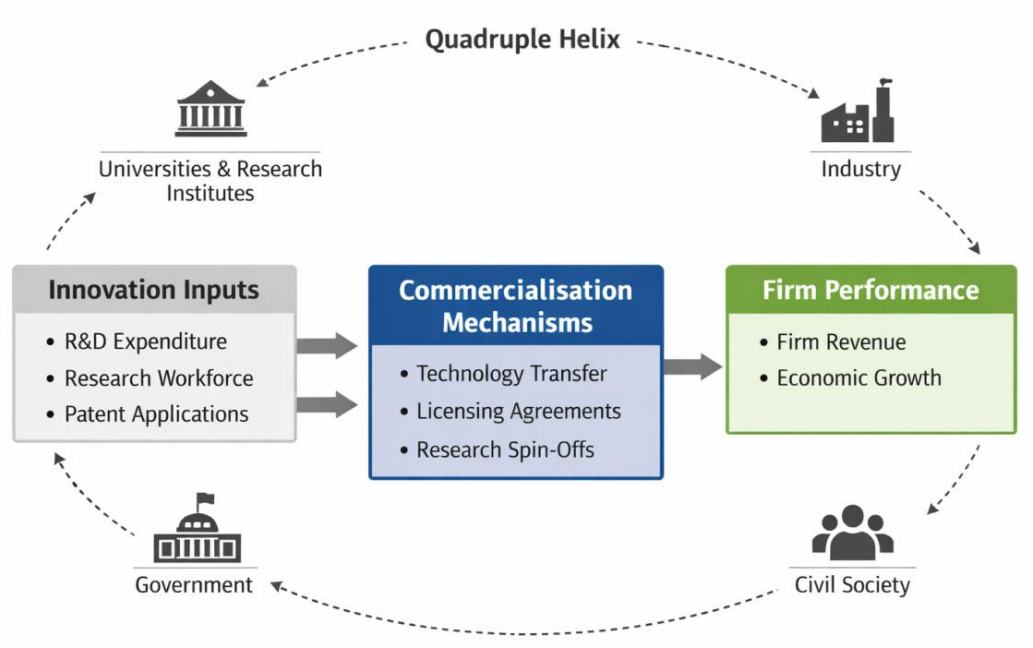

Figure 1. Conceptual framework of innovation inputs, commercialization mechanisms, and firm performance in R&D zones

Figure 1 illustrates the conceptual framework guiding this study. The framework distinguishes between upstream innovation inputs—such as R&D expenditure, research labour, and patenting activity—and downstream commercialisation mechanisms, including technology transfer, licensing, and research-based spin-off formation. These commercialisation mechanisms are positioned as the primary channels through which knowledge generated by universities and research organisations is translated into firm-level economic outcomes. Consistent with the Quadruple Helix perspective, the framework situates these processes within a broader system involving industry, government, and civil society, emphasising that innovation outcomes emerge from interaction rather than from isolated inputs. This conceptualisation informs the selection of variables and the empirical strategy developed in Section 3.

3. Methodology

3.1. Analytical framework and hypotheses

To examine the relationship between industry–university collaboration and regional economic performance, this study adopts an empirical framework consistent with the Quadruple Helix growth perspective outlined in Section 2. Within this framework, regional firm revenue is treated as an observable economic outcome reflecting the combined influence of labour inputs, public expenditure, innovation-related inputs, and collaboration-based commercialisation activities.

The analytical focus is placed on distinguishing upstream innovation inputs from downstream commercialisation outputs. Labour stock is included as a fundamental production factor associated with civil society participation in economic activity. Government expenditure is incorporated to capture the contribution of public-sector investment in regional

economies. Intermediate innovation inputs include R&D expenditure, research personnel, and patent activity, representing knowledge-generation capacity. Finally, industry–university collaboration is operationalised through technology transfer and the formation of research-based spin-offs, reflecting commercialisation-oriented interactions among helix actors.

Based on this framework, four hypotheses are tested:

- H1: An increase in labour stock within R&D zones is positively associated with firm revenue.
- H2: Government expenditure within R&D zones is positively associated with firm revenue.
- H3: Innovation-related intermediate inputs are positively associated with firm revenue.
- H4: Industry–university collaboration activities, particularly technology commercialisation, are positively associated with firm revenue.

3.2. Data and sample

The empirical analysis uses regional panel data from officially published statistical sources for designated R&D zones. The dataset covers four major R&D zones over the period 2013–2022. These zones were selected for their relatively long operational histories and consistent availability of zone-level economic and innovation indicators, which allow for balanced panel estimation.

All monetary variables were converted into real terms using regional consumer price indices (base year = 2020). The resulting dataset comprises 40 observations (four regions over ten years). The unit of analysis is the R&D zone–year, reflecting aggregate economic and innovation activity within each zone.

3.3. Variables and measurement

Firm revenue is used as the dependent variable and measured as the real total revenue of firms operating within each R&D zone.

Independent variables are grouped into four categories corresponding to the Quadruple Helix framework:

1. Labour input (civil society):
   Labour stock is measured as the number of employees engaged in production and management roles within each zone.
2. Public sector input:
   Government expenditure captures real public spending allocated at the regional level.
3. Innovation-related intermediate inputs:
   These include total R&D expenditure, the number of research personnel, and the number of domestic and international patent applications, reflecting regional knowledge-generation capacity.
4. Industry–university collaboration and commercialisation:
   Collaboration is operationalized using three indicators: the number of technology transfer cases, the average technology licensing fee, and the number of research-based spin-off firms established within each zone.

All variables are log-transformed before estimation to reduce skewness and to allow coefficients to be interpreted as elasticity.

3.4. Empirical model

To test the hypotheses, the study estimates a log-linear panel regression model of the following form:

$$\ln(TR_{it}) = \alpha + \beta_1 \ln(LS_{it}) + \beta_2 \ln(G_{it}) + \beta_3 \ln(X_{it}) + \beta_4 \ln(\mathrm{IAC}_{it}) + \varepsilon_{it} \quad (1)$$

where (TR_{it}) denotes firm revenue in region *i* at time *t*; LS_{it} represents labour stock; (G_{it}) denotes government expenditure; (X_{it}) is a vector of innovation-related intermediate inputs; and (IAC_{it}) represents industry–university collaboration indicators.

Given the limited number of regions and the balanced structure of the data, fixed-effects estimation is employed to control for time-invariant regional characteristics. Diagnostic tests were conducted to assess model fit and serial correlation.

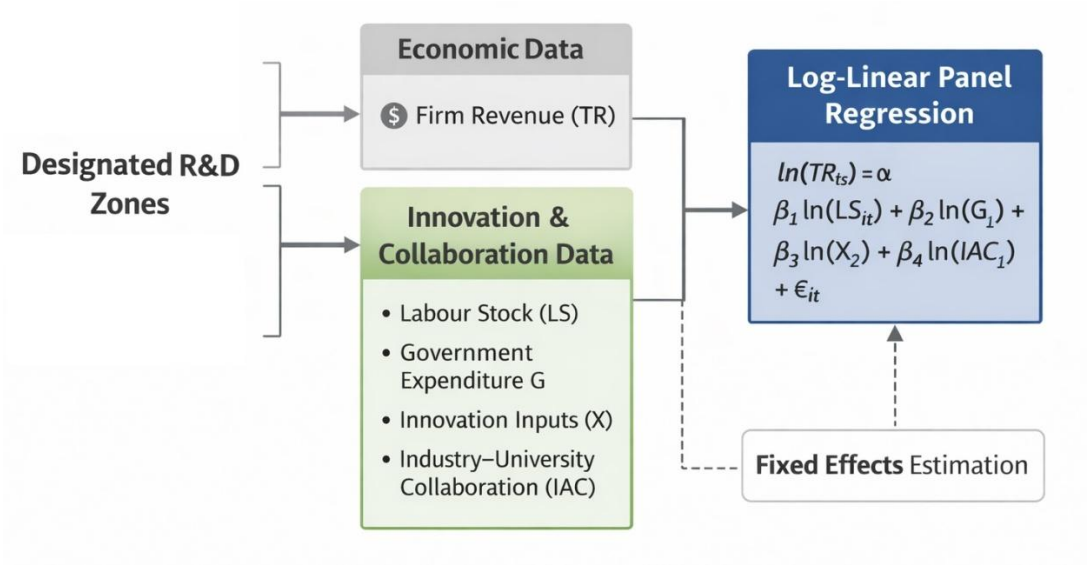

Figure 2. Empirical model linking innovation inputs, commercialization mechanisms, and firm revenue

Figure 2 presents the empirical structure used to estimate the relationships proposed in the conceptual framework. Firm revenue is specified as the dependent variable. In contrast, explanatory variables are organised into four groups: labour inputs, public sector inputs, innovation-related intermediate inputs, and commercialisation-oriented industry–university collaboration indicators. This structure reflects the analytical distinction between upstream research capacity and downstream knowledge utilisation. The model is estimated using a fixed-effects panel approach to control for unobserved, time-invariant regional characteristics, ensuring that the estimated coefficients capture within-region variation over time.

3.5. Analytical strategy

The analysis proceeds in three steps. First, descriptive statistics are examined to assess variation across regions and over time. Second, panel regression estimates are obtained to evaluate the direct effects of labour, public expenditure, innovation inputs, and collaboration variables on firm revenue. Third, the results are interpreted with particular attention to whether collaboration variables oriented toward commercialisation exhibit stronger associations with firm performance than upstream innovation inputs.

This approach is intended to provide a conservative empirical assessment of Quadruple Helix–related mechanisms without attributing causality beyond what the data support.

4. Results

4.1. Descriptive patterns across R&D zones

Table 1 provides an overview of the distribution of economic, innovation, and collaboration variables across the R&D zones and over time. Several patterns are noteworthy. First, firm revenue exhibits substantial dispersion, suggesting marked heterogeneity in economic performance among zones and across years. This heterogeneity provides a suitable empirical context for examining the explanatory contribution of innovation and collaboration variables.

Second, labour stock shows comparatively lower variance than other variables, indicating that employment capacity within the zones is relatively stable. This stability contrasts with the pronounced variation observed in patent activity, technology transfer, and spin-off formation, which display wider ranges and higher standard deviations. These patterns suggest that while baseline production capacity changes gradually, innovation and commercialisation activities are more episodic and potentially sensitive to institutional or policy conditions.

Third, innovation-related inputs, such as R&D expenditure and researcher numbers, exhibit moderate dispersion but do not vary to the same extent as commercialisation indicators. This distinction supports the analytical separation between knowledge-generation capacity and knowledge-utilisation outcomes, which underpins the empirical model. Overall, the descriptive statistics in Table 1 indicate that the dataset contains sufficient variation to examine differentiated effects across input and collaboration categories.

Table 1. Descriptive statistics of analytical variables (R&D zones, 2013–2022)

Variable	Mean	Std. Dev.	Min	Max	Observations
Firm revenue (TR)	11.86	0.47	10.81	12.36	40
Labour stock (LS)	10.15	0.29	9.66	10.85	40
Government expenditure (G)	13.53	0.58	12.38	14.58	40
R&D expenditure (RND)	9.88	0.64	8.35	11.34	40
Researchers (RES)	9.43	0.51	8.76	10.60	40
Patent applications (PAT)	9.12	0.91	7.07	11.09	40
Technology transfers (TT)	6.44	0.78	5.11	7.61	40
Licensing fee (LF)	3.18	0.52	2.30	4.43	40
Research-based spin-offs (SO)	3.31	0.63	2.08	4.28	40

4.2. Bivariate associations and preliminary insights

The correlation matrix presented in Table 2 offers preliminary insight into the relationships among key variables before multivariate estimation. Firm revenue is strongly and positively correlated with labour stock, consistent with its role as a core production input. Positive correlations are also observed between firm revenue and patent applications, technology transfer cases, and research-based spin-offs, suggesting that innovation outputs and commercialisation activities may be associated with improved regional economic performance.

Table 2. Correlation matrix

Variable	TR	LS	G	RND	RES	PAT	TT	LF	SO
TR	1.00								
LS	0.81	1.00							
G	0.12	0.24	1.00						
RND	0.18	0.31	0.55	1.00					
RES	0.22	0.35	0.48	0.67	1.00				
PAT	0.64	0.52	0.19	0.41	0.46	1.00			
TT	0.59	0.44	0.16	0.33	0.37	0.58	1.00		
LF	0.21	0.17	0.09	0.28	0.26	0.32	0.41	1.00	
SO	0.56	0.39	0.14	0.29	0.34	0.55	0.62	0.38	1.00

In contrast, the correlation between firm revenue and government expenditure is weak, and the relationship between firm revenue and R&D expenditure is modest. These patterns suggest that the economic effects of public spending and research investment may not be direct or immediate, reinforcing the importance of examining downstream outcomes rather than relying solely on input measures.

Among independent variables, moderate correlations are observed between patents, technology transfer, and spin-off formation. This clustering is theoretically expected, as these indicators represent sequential or complementary stages within the commercialisation pathway. Importantly, none of the correlation coefficients exceed commonly accepted thresholds for severe multicollinearity. This suggests that the regression estimates are unlikely to be driven by redundant explanatory variables and that the coefficients can be interpreted with reasonable confidence.

4.3. Multivariate results: Core determinants of firm revenue

The fixed-effects panel regression results reported in Table 3 provide the study's main empirical findings. The model explains a large proportion of the within-zone variation in firm revenue over time, and diagnostic statistics do not indicate problematic serial correlation.

Table 3. Fixed-effects panel regression results (dependent variable: firm revenue)

Variable	Coefficient	Std. Error	p-value
Labour stock (LS)	1.18	0.09	<0.001
Government expenditure (G)	−0.11	0.07	0.12
R&D expenditure (RND)	−0.04	0.06	0.43
Researchers (RES)	−0.19	0.12	0.11
Patent applications (PAT)	0.03	0.01	0.03
Technology transfers (TT)	0.15	0.05	0.01
Licensing fee (LF)	0.07	0.05	0.16
Research-based spin-offs (SO)	0.05	0.02	0.02
Constant	1.51	0.14	<0.001

Model statistics:
R^2 = 0.96
Observations = 40
Durbin–Watson = 1.36

Labour stock exhibits a positive and statistically significant coefficient, indicating that increases in employment capacity—specifically production and management personnel—are associated with higher firm revenue within R&D zones. This result is consistent with standard production theory and confirms that labour remains a central determinant of regional economic performance, even in innovation-oriented environments.

Government expenditure does not show a statistically significant relationship with firm revenue. This finding suggests that aggregate public spending, measured at the regional level, does not directly translate into firm-level economic outcomes within R&D zones after accounting for other factors. One interpretation is that public expenditure may operate through indirect or long-term channels not captured in the current specification, or that its effects are mediated by institutional arrangements rather than reflected in contemporaneous revenue measures.

4.4. Innovation inputs versus innovation outputs

A key contribution of the empirical analysis lies in differentiating between innovation inputs and innovation outputs. Among the innovation-related intermediate inputs, patent applications are positively and significantly associated with firm revenue. This finding suggests that codified innovation outputs that are closer to potential commercial use are more strongly linked to economic performance than upstream research inputs.

In contrast, neither R&D expenditure nor the number of researchers exhibits a statistically significant association with firm revenue. This result does not imply that research inputs are unimportant; rather, it indicates that their economic relevance is not immediately observable at the aggregate firm-revenue level. The absence of significance may reflect time lags between research investment and commercial outcomes, or the fact that research activity contributes to broader capability building that is not fully captured by short-term revenue measures.

Taken together, these findings reinforce the analytical distinction between knowledge creation and knowledge exploitation. They suggest that regional economic performance is more closely associated with outputs that signal readiness for market application than with inputs that reflect research capacity alone.

4.5. Commercialization and industry–university collaboration effects

The collaboration-related variables provide further insight into how public research activity is translated into economic outcomes. As shown in Table 3, both the number of technology transfer cases and the number of research-based spin-offs are positively and statistically significantly associated with firm revenue. These results indicate that regions with more frequent commercialisation interactions between research organisations and firms tend to exhibit higher levels of aggregate firm revenue.

In contrast, the average licensing fee does not show a statistically significant effect. This finding suggests that the scale or monetary value of individual transactions is less important than the presence and continuity of commercialisation activity. In other words, repeated engagement in technology transfer and entrepreneurial formation may contribute more to regional economic performance than isolated high-value licensing deals.

This pattern is consistent with an interpretation of collaboration as a cumulative and relational process rather than a series of discrete financial transactions. Frequent technology transfer and spin-off formation may foster learning, capability development, and network effects, reflected in broader firm performance within the zone.

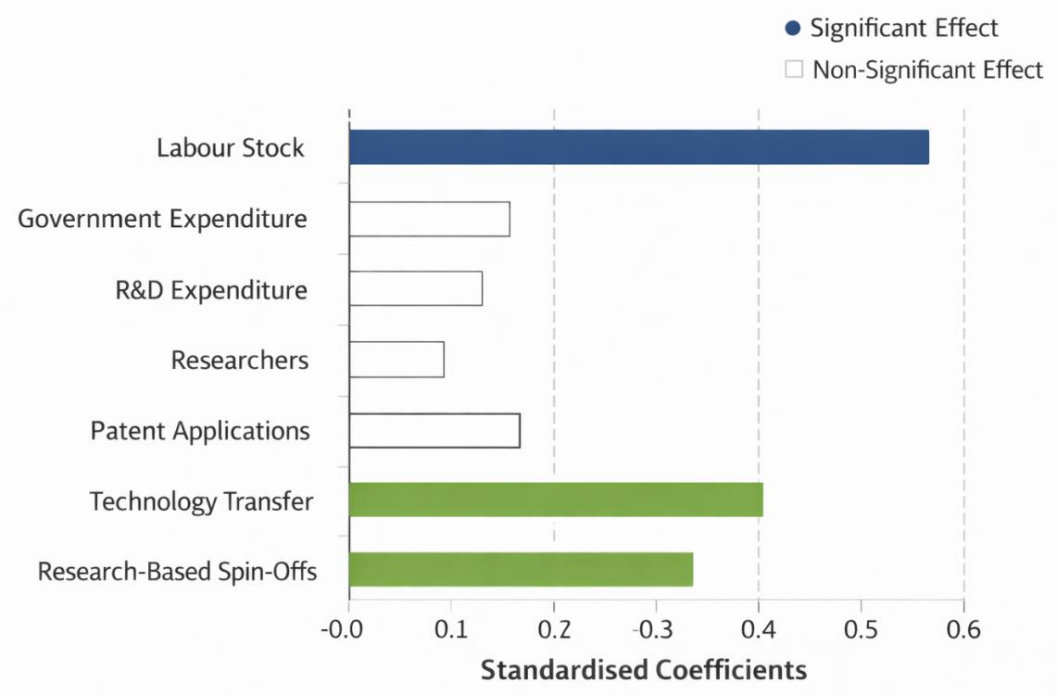

Figure 3. Comparison of standardized effects on firms' revenue across innovation inputs and commercialization

Figure 3 summarises the relative strength of the estimated effects on firm revenue by presenting standardised coefficients from the fixed-effects regression model. The figure highlights that labour stock and commercialisation-oriented variables—particularly technology transfer and research-based spin-off formation—exhibit the strongest positive associations with firm revenue. In contrast, upstream innovation inputs, such as R&D expenditure and researcher numbers, exhibit weaker, statistically insignificant effects. By visually contrasting these estimates, the figure reinforces the empirical distinction between knowledge-generation capacity and knowledge-utilisation mechanisms identified in the regression results.

4.6. Integrated interpretation of results

Synthesising the evidence presented in Tables 1 to 3, several conclusions can be drawn. First, labour inputs and collaboration variables oriented toward commercialization show the most consistent and robust associations with firm revenue. Second, innovation outputs that are closer to market application—patents, technology transfer, and spin-offs—appear more economically salient than upstream R&D inputs. Third, aggregate public expenditure does not exhibit a direct association with firm revenue within the observed period.

These findings suggest that the economic contribution of public research within R&D zones is most clearly observed when knowledge is actively translated into commercial activity. Rather than supporting a simple input–output relationship between research investment and economic growth, the results point to the importance of intermediate commercialisation mechanisms as the link between innovation systems and regional economic outcomes.

4.7. Robustness and sensitivity checks

To assess the robustness of the main findings, a series of supplementary analyses was conducted. First, alternative model specifications were estimated by sequentially excluding groups of explanatory variables. The key coefficients associated with labour stock, patent applications, technology transfer activity, and research-based spin-off formation remained stable in sign and statistical significance across these specifications, indicating that the inclusion of any single covariate category does not drive the results.

Second, sensitivity to potential scale effects was examined by re-estimating the model using per-firm and per-employee normalisations of selected variables. While the magnitudes of the coefficients changed as expected under alternative scaling, the relative importance of the commercialisation-oriented collaboration variables was preserved. In particular, technology transfer and spin-off activity continued to exhibit positive associations with firm revenue under these alternative specifications.

Third, to account for potential time-related influences, models including year fixed effects were estimated. The inclusion of year controls did not materially alter the estimated coefficients of the main explanatory variables, suggesting that common macroeconomic shocks or period-specific effects do not drive the results.

Finally, given the relatively small number of regions, additional checks were conducted using heteroskedasticity-robust standard errors. The statistical significance of the main coefficients of interest was unaffected, providing further confidence in the reliability of the reported estimates.

Overall, these robustness checks suggest that the core findings are not sensitive to reasonable variations in model specification or estimation approach and can be interpreted as stable within the limits of the available data.

5. Discussion

5.1. Interpretation of main findings

This study examined the relationship between industry–university collaboration and regional firm performance within designated R&D zones, drawing on a Quadruple Helix–informed empirical framework. The results indicate that labour stock and commercialisation-oriented collaboration variables—specifically technology transfer activity and research-based spin-off formation—are positively associated with firm revenue. In contrast, aggregate government expenditure and several upstream R&D input measures do not exhibit statistically significant relationships with firm revenue after controlling for other factors.

These findings suggest that the economic relevance of public research activity is most clearly observed at the point where knowledge is translated into market-facing applications. Rather than supporting a simple input-driven view of regional innovation, the results align with perspectives that emphasise the importance of intermediate mechanisms linking research capacity to economic outcomes. In this sense, the findings reinforce the analytical distinction between knowledge creation and knowledge utilisation introduced in Sections 1 and 2.

5.2. Commercialization as the salient quadruple helix mechanism

The positive associations observed for technology transfer and spin-off formation highlight the role of commercialisation as a practical manifestation of Quadruple Helix interaction. These activities represent concrete points of engagement among universities, firms, and

supporting institutions, in which research outputs are adapted to commercial contexts. The absence of a significant effect for average licensing fees suggests that the frequency and continuity of commercialisation interactions are more important for regional economic performance than the financial scale of individual transactions.

Importantly, the robustness checks reported in Section 4.7 indicate that these relationships are not sensitive to alternative model specifications, variable scaling, or the inclusion of year fixed effects. The stability of the commercialisation coefficients across these checks strengthens confidence in the interpretation that collaboration outcomes oriented toward market application are consistently associated with firm revenue within the observed settings.

5.3. Innovation inputs, time horizons, and economic outcomes

The lack of statistically significant effects for R&D expenditure and researcher numbers should be interpreted with caution. These inputs are fundamental to innovation systems, but their economic impact may be indirect or realised over longer time horizons than those captured by contemporaneous revenue measures. The robustness analysis suggests that their non-significance is not an artefact of model specification, but rather reflects the empirical reality of the dataset.

This pattern is consistent with the view that upstream research investments contribute to regional development primarily through intermediate outputs—such as patents, technology transfer, and entrepreneurial activity—rather than through immediate financial returns. The finding that patent applications retain significance, even when alternative specifications are considered, supports this interpretation by positioning patents as a transitional output between research activity and commercial exploitation.

5.4. Public expenditure and contextual effects

Aggregate government expenditure does not exhibit a direct association with firm revenue in the estimated models. The robustness checks, including specifications with year fixed effects and alternative scaling, suggest that this result is not driven by omitted temporal factors or heteroskedasticity. Public spending may exert its influence through institutional development, infrastructure provision, or capability-building processes that are not directly reflected in short-term firm revenue.

This finding highlights the importance of distinguishing between direct and indirect economic effects when evaluating regional innovation policy instruments. It also reinforces the value of focusing empirical analysis on observable interaction outcomes, rather than assuming that public investment will automatically translate into firm-level economic performance.

5.5. Implications of robustness findings for interpretation

The inclusion of robustness and sensitivity checks adds an important layer of credibility to the empirical results. The consistency of key coefficients across alternative specifications suggests that the main conclusions are not driven by modelling choices or idiosyncratic features of the data. At the same time, the robustness analysis does not eliminate the inherent limitations associated with small regional samples and aggregate-level measurement.

Accordingly, the findings should be interpreted as identifying stable associations rather than causal effects. Within these bounds, the results provide a coherent empirical narrative: regional firm performance within R&D zones is more closely associated with labour capacity

and commercialisation-oriented collaboration than with upstream research inputs or aggregate public expenditure.

6. Conclusion

This study examined whether industry–university collaboration is associated with regional firm performance within designated R&D zones, using an empirical framework informed by the Quadruple Helix perspective. By distinguishing between upstream innovation inputs and downstream commercialisation outcomes, the analysis sought to clarify which aspects of collaboration are most closely linked to observable economic performance.

The findings indicate that labour stock and collaboration activities oriented toward commercialisation—specifically, technology transfer and research-based spin-off formation—are positively associated with firm revenue. In contrast, aggregate government expenditure and several upstream R&D input measures do not exhibit statistically significant relationships with firm revenue after controlling for other factors. These patterns are robust to alternative model specifications, scaling choices, and the inclusion of temporal controls, suggesting that particular estimation assumptions do not drive the results.

Taken together, the evidence points to the importance of knowledge utilisation mechanisms in translating public research activity into regional economic outcomes. While research capacity and public investment remain essential components of innovation systems, their economic relevance is most evident when they are linked to repeated and sustained commercialisation interactions. The stability of the commercialisation coefficients across robustness checks reinforces the interpretation that frequency and continuity of collaboration may matter more than the financial scale of individual transactions.

At the same time, the absence of direct effects for some innovation inputs and public expenditure highlights the limits of short-term or aggregate measures in capturing the broader contributions of research and policy interventions. These elements may exert influence through longer-term capability development, institutional learning, or indirect spillovers that are not fully reflected in contemporaneous firm revenue.

In conclusion, this study contributes to the empirical literature on regional innovation systems by providing evidence that commercialisation-oriented industry–university collaboration constitutes a consistent and measurable link between public research activity and regional firm performance. By integrating robustness checks into the analysis, the study offers a cautious yet stable empirical account of these relationships, providing a foundation for future research that further examines temporal dynamics, causal mechanisms, and variation across regional contexts.

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