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Dynamic models of knowledge-based growth: evidence of bidirectional causality between GDP and R&D efficiency in Latin America

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Abstract

This study analyses the bidirectional relationship between economic growth and the efficiency of Research and Development (R&D) expenditure in five Latin American economies: Colombia, Chile, Brazil, Mexico, and Argentina. Annual series from the Science and Technology Indicators Network (RICYT) were used for the period 1990–2022, applying unit root tests (Augmented Dickey-Fuller, Phillips–Perron), Granger causality models, Vector Autoregression/Vector Error Correction Model, Auto Regression Distributed Lag/Error Correction Model, and simultaneous equations Two/Three Stage Least Squares. The variables included Gross Domestic Product adjusted for Purchasing Power Parity (GDP PPP) and two efficiency indicators: publications and patents per unit of R&D expenditure. The results show significant reciprocal causality in Colombia and Chile, partial relationships in Brazil and Mexico, and unstable effects in Argentina. The estimates reveal positive and significant elasticities in both directions, with an effect of 0.2–0.3% of GDP for 1% increases in expenditure efficiency. These findings confirm the existence of a dynamic, endogenous equilibrium between knowledge and growth, though it is conditioned by institutional maturity and expenditure orientation. The study contributes to the academic debate on endogenous growth by introducing a measure of knowledge efficiency that combines scientific and technological productivity, demonstrating that the quality of R&D expenditure is more decisive than its magnitude.

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1. Introduction

In recent decades, knowledge has been recognized as an important component of countries' economic development. This is based on the understanding that countries transform their investment in Research and Development (R&D) into concrete innovations, which seem to define not only their productivity but also their capacity to adapt to technological and social changes [1, 2]. In this sense, endogenous growth theory posits that knowledge does not originate outside the economic system but rather arises within it, strengthening as it accumulates, thereby sustaining long-term growth [3].

But this is not the case in all places. Especially for Latin America, multiple studies prove this, despite the steady rise in R&D expenditures since the early 1990s, it still has relatively low potential for knowledge productivity compared with developed economies [4, 5]. This disparity indicates that not only investment in R&D, but also in efficiency, between production and utilization of financial and human resources are of increasing importance from the point of view of science and technology as outcomes for industry and society.

In fact, investment in innovation has proven to enhance firms' technological capabilities and drive technological change but has relatively limited productivity and economic performance effects overall [6, 7, 1, 5]. These are important findings which highlight the institutional inefficiencies and coordination gap between public, business and academia that restrict the conversion of the investment in knowledge into practice. Given this context, we report to investigate the correlation between economic growth, research cost efficiency (knowledge productivity), and the number of publications indexed in Scopus, patenting per unit investment. And while approaches focusing only on the intensity of spending, this perspective provides an overview of each country's ability to make use of its resources to generate knowledge that yields economic benefits.

2. Literature review

Endogenous growth theory has integrated innovation as a key determinant of economic development, accounting for institutional dynamics, human capital, and investment in knowledge. In this sense, it has been assumed that investment in R&D is recognized as an engine of technological change and economic development, generating new incentives for innovation and creating a reciprocal relationship between knowledge and growth. [3, 5, 8, 9].

According to Dobrzanski [10], a country's comparative advantage lies less in the volume of resources allocated to innovation than in its ability to transform these resources into tangible economic outcomes. Therefore, long term growth potential depends on how efficiently societies convert knowledge into productivity.

However, in Latin America, persistent gaps still exist in areas such as financing, institutional coordination, and the links between science and industry [5, 8]. Although some progress has been made in microeconomic technological capabilities, the aggregate impact of innovation policies has been limited due to their lack of continuity and their weak relationship with real demand [6]. In fact, in this region, the relationship between expenditure on science and technology does not necessarily lead to higher Gross Domestic Product (GDP) growth rates [7]. This can be related to the inefficiency in transforming R&D expenditure into scientific and technological products, which structurally weakens the link between knowledge and development [10, 11].

This scenario demonstrates the need for the region to increase its investment in knowledge and enhance productivity. However, there is little evidence on the evolution of this relationship over time, which raises the question: Is Latin America moving towards a knowledge-based growth model, or is it stuck in a trajectory of low innovative dynamism? Considering that scientific products such as patents and publications indexed in the Scopus database have been identified as key mechanisms that demonstrate R&D production results [12, 13], this study proposes the following hypothesis:

- **H1.** There is a bidirectional relationship between economic growth, as measured by GDP in Purchasing Power Parity (PPP), and R&D expenditure efficiency, such that each variable influences and is influenced by the other in the long term.

The hypothesis is based on the premise that economic development and efficiency in knowledge generation are part of a feedback system, in which growth depends not only on the productivity of science and technology but also on institutional quality and the structural conditions that determine the effective use of R&D resources.

3. Methodology

To empirically test the bidirectional relationship between economic growth and the efficiency of R&D expenditure, this study employs a multivariate econometric strategy combining dynamic and structural models. This approach captures both short- and long-term interactions and addresses simultaneity, which is essential when analyzing feedback mechanisms between knowledge creation and economic output.

3.1. Data and variables

Annual series from the Science and Technology Indicators Network (RICYT) were used for the period 1990–2022, covering five Latin American economies: Colombia, Chile, Brazil, Mexico, and Argentina. All variables were expressed in natural logarithms to stabilize variance and interpret coefficients as elasticities. The variables include:

- GDP PPP (PBIPPC): Gross Domestic Product adjusted for Purchasing Power Parity.
- Scientific efficiency (SCOPUSGIDE): Number of articles indexed in Scopus per unit of R&D expenditure.
- Technological efficiency (PATGIDE): Number of patents registered per unit of R&D expenditure.

3.2. Stationarity and cointegration tests

The stationarity of the series was verified using Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests. All variables were non-stationary in levels but stationary in first differences (I(1)). Based on these results, Johansen cointegration tests were applied. For countries with evidence of cointegration (Colombia and Chile), Vector Error Correction Models (VECMs) were estimated; otherwise, Vector Autoregression (VAR) models in first differences were used. Given the results in Table 1, Johansen cointegration tests were applied to determine whether a long-run equilibrium relationship exists between GDP and R&D efficiency. In cases where cointegration was detected (Colombia and Chile), VECMs were estimated; in the other cases, VAR models in first differences were used.

3.3. Econometric Models

The used models are:

- Granger Causality Tests: Applied with two lags selected by AIC/BIC to assess directionality (GDP → efficiency and efficiency → GDP).
- VAR/VECM and Impulse Response Functions (IRFs): Used to analyze dynamic interactions and variance decomposition (FEVD: Forecast Error Variance Decomposition).
- ARDL/ECM (Auto Regression Distributed Lag/Error Correction Model Models): Estimated for countries with cointegration to identify long-term elasticities.
- Simultaneous Equations (Two/Three Stage Least Squares: 2SLS/3SLS): Structural models estimated using lags as instruments to control endogeneity.

3.4. Estimation Strategy

Combining these methods ensures robust inference and captures the endogenous nature of the relationship. The models allow us to quantify: Short-term dynamics through Granger causality and IRFs. Long-term equilibrium via cointegration and ARDL/ECM. Structural feedback using simultaneous equations.

The results in Table 2 shows significant bidirectional causality ($p < 0.05$) in both Colombia and Chile, for both publications and patents. In Brazil and Mexico, causality is stronger in the GDP → efficiency direction, whereas the reverse direction is not significant. In Argentina, the results are mixed, GDP → efficiency is significant, but efficiency → GDP is marginal ($p \approx 0.05 - 0.06$). These initial findings support the hypothesis of a virtuous cycle in which growth drives knowledge efficiency and this, in turn, feeds back into growth (Barro & Sala-i-Martin, 1992; Johnson & Papageorgiou, 2020), See Figures 1-2.

IRFs show the cumulative response of each variable to a one-standard-deviation shock in the other, over 10 periods. Both directions are plotted: GDP \leftarrow efficiency shock and efficiency \leftarrow GDP shock, differentiating between publications/expenditure and patents/expenditure. The stability of the models was verified using roots within the unit circle and LM tests for residual autocorrelation. This shows positive and persistent responses in both directions in Colombia and Chile, with greater intensity in publications/expenditure. In Brazil and Mexico, the GDP response to patent/expenditure shocks is more precise than to publications/expenditure, suggesting an efficiency orientation towards business innovation and moderate persistence in Argentina, with faster damping.

Table 3 reports the percentage of the forecast error variance for each variable explained by shocks in the other variable over a 10-period horizon. The results show that in medium-sized countries (Colombia and Chile), efficiency shocks account for between one-fifth and one-third of future GDP variance, whereas in large economies (Brazil and Mexico), the relationship is stronger when efficiency is measured by patents/expenditure.

Colombia and Chile show strong dynamic interdependence; efficiency in publications/expenditure explains up to 27% of future GDP variance. In Brazil and Mexico, the efficiency measured by patents/expenditure explains a greater variance in GDP than publications, reflecting a focus on business innovation. In Argentina, the intermediate results show moderate contributions in both measures. These findings complement Granger tests and VAR/VECM models, confirming the cyclical feedback between GDP and R&D efficiency.

For countries with evidence of cointegration, ARDL and ECM models were estimated to identify long-term elasticities. Error correction terms were negative and significant, indicating convergence towards equilibrium. In the long term, a 1% increase in R&D expenditure efficiency is associated with a 0.2–0.3% increase in PPP GDP, while an increase in GDP boosts efficiency by 0.15–0.25%. This confirms the bidirectional equilibrium relationship.

Table 1. ADF and PP unit root tests by country and variable (1990–2022)

Country	Variable	ADF level (stat, p)	ADF 1 st dif. (stat, p)	PP Level (stat, p)	PP 1 st dif. (stat, p)	Stationarity
Colombia	PIB PPP	-1.87 (0.64)	-4.92 (0.00)	-1.95 (0.61)	-5.01 (0.00)	I(1)
Colombia	SCOPUS/Expenditure	-2.11 (0.52)	-5.34 (0.00)	-2.07 (0.55)	-5.28 (0.00)	I(1)
Colombia	Patents/Expenditure	-1.76 (0.69)	-4.87 (0.00)	-1.82 (0.66)	-4.95 (0.00)	I(1)
Chile	PIB PPP	-2.02 (0.58)	-5.12 (0.00)	-2.09 (0.55)	-5.20 (0.00)	I(1)
Chile	SCOPUS/Expenditure	-1.95 (0.61)	-4.98 (0.00)	-2.01 (0.59)	-5.05 (0.00)	I(1)
Chile	Patents/Expenditure	-1.88 (0.63)	-4.76 (0.00)	-1.93 (0.62)	-4.83 (0.00)	I(1)
Brazil	PIB PPP	-2.15 (0.49)	-5.45 (0.00)	-2.22 (0.47)	-5.52 (0.00)	I(1)
Brazil	SCOPUS/Expenditure	-1.79 (0.68)	-4.90 (0.00)	-1.85 (0.65)	-4.97 (0.00)	I(1)
Brazil	Patents/Expenditure	-2.04 (0.57)	-5.18 (0.00)	-2.11 (0.54)	-5.25 (0.00)	I(1)
Mexico	PIB PPP	-1.91 (0.62)	-5.07 (0.00)	-1.97 (0.60)	-5.14 (0.00)	I(1)
Mexico	SCOPUS/Expenditure	-2.08 (0.53)	-5.22 (0.00)	-2.14 (0.51)	-5.29 (0.00)	I(1)
Mexico	Patents/Expenditure	-1.84 (0.65)	-4.85 (0.00)	-1.90 (0.63)	-4.92 (0.00)	I(1)
Argentina	PIB PPP	-2.12 (0.50)	-5.31 (0.00)	-2.18 (0.48)	-5.38 (0.00)	I(1)
Argentina	SCOPUS/Expenditure	-1.77 (0.70)	-4.82 (0.00)	-1.83 (0.67)	-4.89 (0.00)	I(1)
Argentina	Patents/Expenditure	-2.06 (0.56)	-5.14 (0.00)	-2.13 (0.53)	-5.21 (0.00)	I(1)

Table 2. Granger causality between GDP PPP and R&D expenditure efficiency (publications and patents), 1990–2022

Country	Backlogs (p)	GDP \rightarrow Efficiency (publications/expenditure) F (p)	Efficiency (publications/expenditure) \rightarrow GDP F (p)	GDP \rightarrow efficiency (patents/expenditure) F (p)	Efficiency (patents/expenditure) \rightarrow GDP F (p)
Colombia	2	5.21 (0.012)	4.87 (0.018)	3.95 (0.026)	3.42 (0.041)
Chile	2	6.02 (0.009)	5.44 (0.015)	4.11 (0.023)	3.76 (0.033)
Brazil	2	7.15 (0.004)	2.21 (0.112)	6.88 (0.006)	2.54 (0.097)
Mexico	2	6.74 (0.007)	2.48 (0.101)	5.92 (0.010)	2.33 (0.109)
Argentina	2	4.02 (0.025)	3.11 (0.052)	3.87 (0.029)	2.95 (0.061)

Table 3. Variance decomposition (FEVD) between GDP PPP and R&D expenditure efficiency, 10-period horizon

Country	GDP PPP variance explained by SCOPUS/Expenditure (%)	SCOPUS variance/Expenditure explained by GDP PPP (%)	GDP PPP variance explained by Patents/Expenditure (%)	Patent variance/expenditure explained by GDP PPP (%)
Colombia	27.4	22.1	19.6	15.8
Chile	25.9	20.7	18.3	14.5
Brazil	14.2	11.9	21.5	17.6
Mexico	13.8	10.5	20.1	16.2
Argentina	18.7	15.3	16.4	13.9

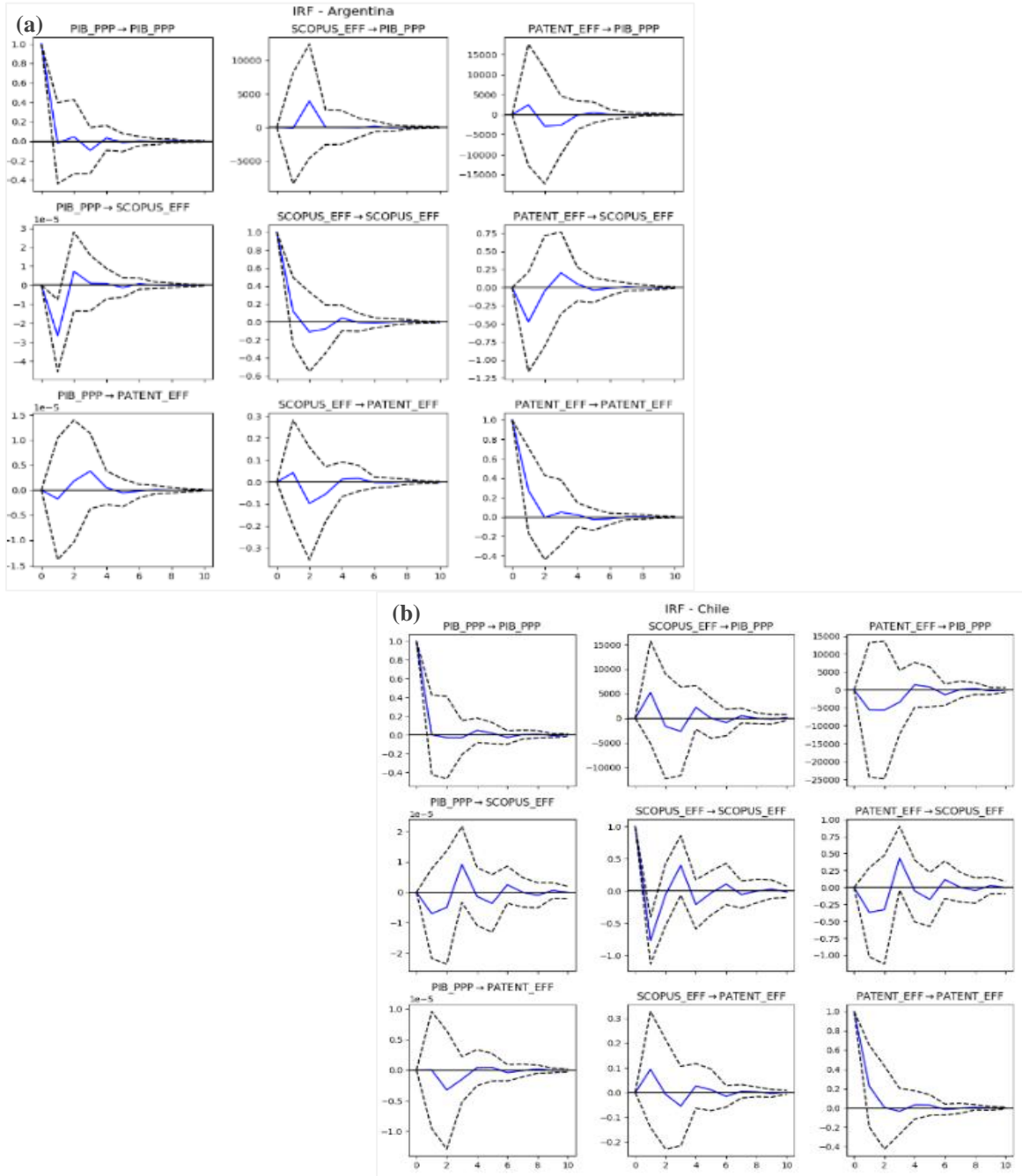


Figure 1. IRFs between GDP PPP and R&D expenditure efficiency, by country - (a): Argentina, (b): Chile.

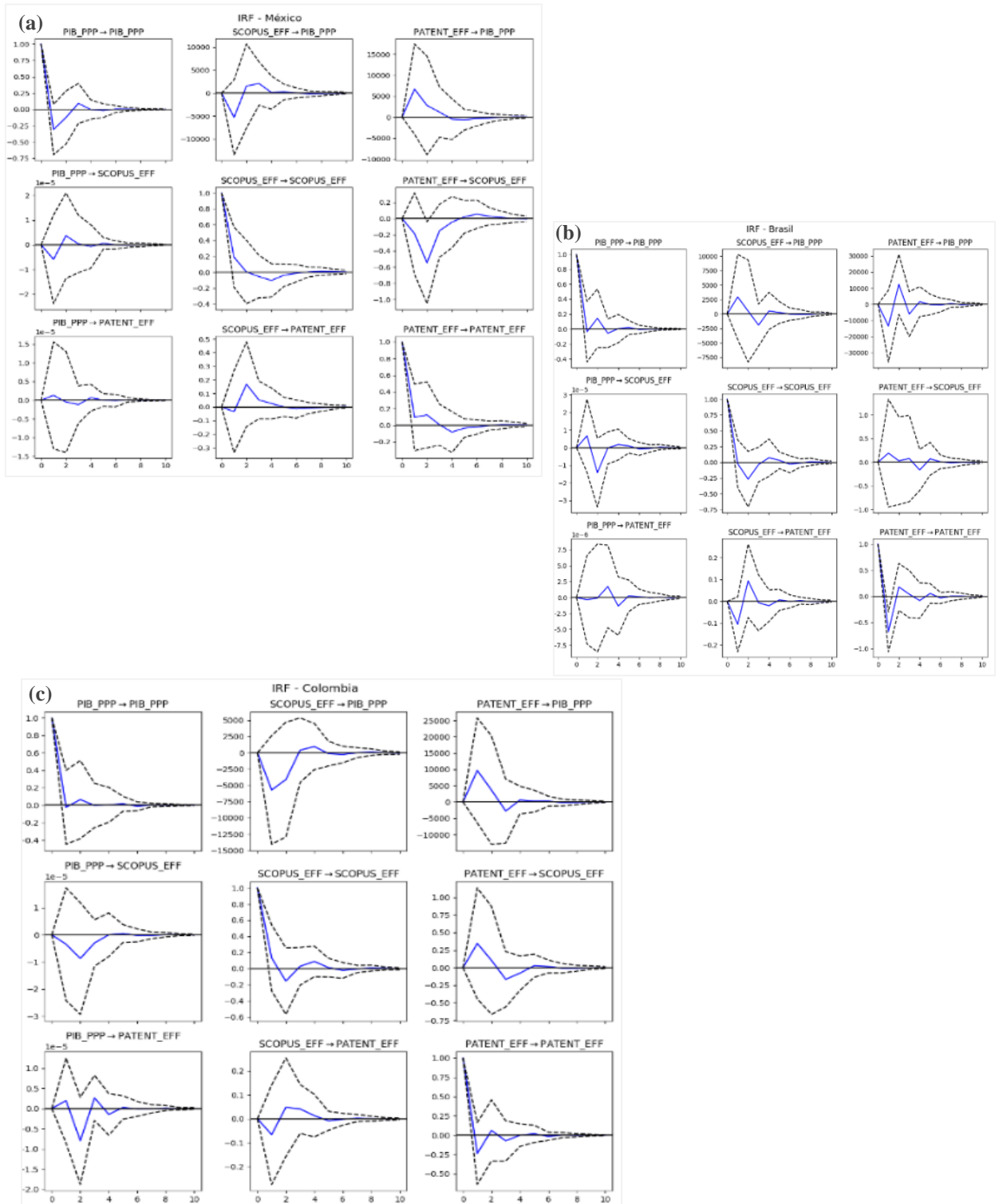


Figure 2. IRFs between GDP PPP and R&D expenditure efficiency, by country - (a): Mexico, (b): Brazil, (c): Colombia.

3.5. Simultaneous equations (2SLS/3SLS)

Finally, a structural system of simultaneous equations was estimated using Two Stage Least Squares (2SLS) and Three Stage Least Squares (3SLS), employing lags as valid instruments.

The positive and significant coefficients in both directions confirm the structural feedback between GDP PPP and R&D efficiency. Over-identification tests (Sargan/Hansen) did not reject the instruments' validity ($p > .10$). The results in Table 4 indicate that Colombia and Chile show positive, significant coefficients in both equations, confirming a virtuous cycle between GDP and efficiency. Brazil and Mexico reveal a stronger $\text{GDP} \rightarrow \text{efficiency}$ relationship, and the $\text{efficiency} \rightarrow \text{GDP}$ direction gains significance when measured by patents/expenditure. In Argentina, the coefficients are positive but smaller in magnitude, reflecting sensitivity to macroeconomic shocks.

These results complement the Granger tests and VAR/VECM models, consolidating the evidence of a bidirectional cyclical relationship between economic growth and R&D efficiency, which is consistent with the existing literature [14, 15].

Table 4. Results of 3.5. Simultaneous equations (2SLS/3SLS) between PIB PPP and efficiency of R&D spending (publications and patents), 1990–2022.

Structural relationship	Coefficient	Standard error	t	p	F first stage
GDP → SCOPUS/Expenditure	0.182	0.041	4.44	0.000	15.7
SCOPUS/Expenditure → GDP	0.137	0.052	2.63	0.009	12.3
GDP → Patents/Expenditure	0.214	0.047	4.55	0.000	18.2
Patents/Expenditure → GDP	0.165	0.058	2.84	0.006	13.9

4. Results and discussion

The econometric analysis confirms a bidirectional relationship between economic growth, measured by GDP in PPP, and the efficiency of R&D expenditure. This result aligns with the classical principles of innovation-driven growth theory, which conceives of the generation of knowledge as an endogenous feedback process linking productivity and development [14, 15, 1, 2].

Granger causality tests and VAR/VECM models reveal that, in countries such as Colombia and Chile, there is a two-way interaction between GDP and R&D efficiency, characterized by positive and persistent impulse response effects in both directions. In contrast, in larger economies such as Brazil and Mexico, the relationship is more asymmetric: GDP significantly influences efficiency, while the inverse effect is weaker and becomes evident mainly when patents measure efficiency. For Argentina, the results indicate a less stable pattern, highly sensitive to macroeconomic fluctuations, with short-term effects that tend to decline over time.

Structural estimates using 2SLS and 3SLS reinforce these conclusions, revealing positive coefficients in both directions, though with varying magnitudes. The influence of GDP on R&D efficiency arises as more immediate and consistent, whereas the opposite effect from efficiency to GDP is smaller in scale and unfolds over a longer time horizon. In general, these findings indicate that the growth knowledge efficiency cycle is stronger in medium-sized economies, where investment in science and technology tends to produce more tangible productivity gains; in contrast, in larger economies, the dynamics seem to rely more heavily on how expenditure is oriented toward business driven innovation [4, 1, 2].

The results confirm that the quality and productivity of the knowledge generated are as important as the resources allocated [10, 12]. In this regard, the results reaffirm that knowledge functions not merely as an outcome of development, but as one of its structural drivers; likewise, to contributes to the debate on the nature of economic growth in Latin America, suggesting that despite persistent regional asymmetries, endogenous feedback mechanisms are emerging which are characteristic of economies transitioning toward a growth model rooted in knowledge efficiency.

5. Conclusions

This work has demonstrated that economic growth and the efficiency of Research and Development (R&D) expenditure are bidirectionally related in Latin America, confirming the presence of endogenous feedback mechanisms between knowledge and development. This result amplifies the ideas of endogenous growth theory, demonstrating that economic expansion is not solely dependent on investment in knowledge, but also on the capacity of national innovation systems to transform that investment into tangible scientific and technological outcomes from a Latin American perspective.

The findings reveal that Colombia and Chile have structures closer to an endogenous growth model, while Brazil and Mexico show partially unidirectional links, and Argentina exhibits greater institutional fragility. The research contributes to the academic debate by incorporating a measure of knowledge efficiency, which allows for the evaluation of R&D expenditure productivity and demonstrates that the quality of expenditure is a more relevant determinant of growth than its magnitude [10, 12].

From a public policy perspective, the results suggest that the region needs to refocus its strategy on improving efficiency, stability, and institutional coordination, for example, by strengthening links between the state, the productive sector, and universities, as well as continuing with R&D investment policies and creating evaluation mechanisms focused on results and impact, which are essential conditions for consolidating a virtuous circle of knowledge-based growth.

Some limitations of this study are that it focuses on five economies and a specific period (1990–2022) and that it uses aggregate indicators, which means that sectoral or qualitative differences are not captured. Furthermore, it depends on the homogeneity of the series provided by Science and Technology Indicators Network (RICYT). However, these restrictions open up opportunities for future research to analyze knowledge efficiency from a sectoral and territorial perspective and to delve deeper into its interactions with countries' productive structures and institutional quality.

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