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Article

Influence of knowledge development and technological innovation on regional progress in Shanghai

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Abstract: This study examines the impact of education quality and innovative activities on economic growth in Shanghai through international trade and fixed asset formation. The study examines how higher education quality and innovation activities drive regional economic growth, with a focus on the mediating effects of international trade and fixed asset formation in Shanghai. The study adopts a quantitative approach utilizing panel data from 31 provinces in China covering the period from 1999 to 2022. The study incorporates variables such as education quality, innovation capacity, and GDP per capita, as well as control variables like labor, capital, and infrastructure. The methodology involves multiple regression models and robustness tests to verify the relationships between and effects of education quality and innovation with regard to economic growth. This study analyzes the direct and indirect effects of university R&D expenditure and innovation on economic growth using a regression model, based on data from 2014 to 2022 in relation to Shanghai. The model introduces variables such as international trade, capital formation, and urbanization to analyze the relationship between higher education quality and economic growth.

Keywords: international trade; fixed capital formation, number of patents; university R&D expenditure; time factor; economic growth; educational quality; innovation activities

1. Introduction

In the past decade, the acceleration of globalization and rapid advancements in science and technology have brought the quality of education and the impact of innovation activities on regional economic growth in China to the forefront of academic and policy discussions (Dubiei, 2020). According to the World Bank, global R&D expenditure has increased by nearly 20% over the past decade, and tertiary education enrollment has risen significantly (Shi et al., 2014). However, significant disparities in economic performance across regions suggest that education quality and innovation activities play crucial roles in driving economic growth. In the context of Shanghai—a leading city in technological and economic development—it is particularly important to explore how education quality and innovation activities influence economic growth (Fan et al., 2020).

Although previous studies have examined the impact of scientific and technological progress and structural changes on economic growth, specific factors such as time and regional variations have often been overlooked when analyzing the roles of educational quality and innovation activities (Ajibike and Fagbemi, 2022).

Moreover, few studies have considered control variables like total fixed assets, housing size, and the number of healthcare facilities when assessing regional economic development, which limits the explanatory power and practical applicability of their findings (Xia et al., 2022).

This study focuses on the Shanghai region, which represents the forefront of economic openness in mainland China, to investigate the influence of education quality and university R&D expenditures on regional economic growth. By incorporating mediating variables such as international trade and fixed capital formation, the study aims to reveal the specific roles of these factors on economic growth across different years and regions from 2014 to 2022.

Based on economic growth theory and innovation-driven theory, an integrated model is constructed with several control variables. The model not only examines the direct impact of education quality and innovation activities on economic growth but also introduces international trade and fixed capital formation as mediating variables (Zhylinska et al., 2024). By systematically analyzing the pathways of these variables, the study seeks to understand how education and innovation contribute to economic growth through various mechanisms and how these mechanisms differ across regions and over time.

The central questions of this study are as follows:

1) To what extent does international trade mediate the impacts of education quality and innovation activities on economic growth in Shanghai?
2) How do the complex effects of fixed capital formation in Shanghai influence different economic indicators and real economic output?

To address these questions, the following hypotheses are formulated:

Hypothesis 1: International trade, measured by the logarithm of Shanghai's total imports and exports, significantly enhances the positive impacts of education quality (measured by university R&D expenditure) and innovation activities (measured by the number of patents) on Shanghai's economic growth.

Hypothesis 2: Fixed capital formation in Shanghai (measured by the logarithm of gross fixed capital formation) has a complex impact on economic output. It negatively affects some economic indicators (e.g., primary income) but positively affects others (e.g., profits), reflecting different manifestations of capital use efficiency in various economic outputs.

Hypothesis 3: Over time, the time factor has a significant negative impact on economic growth in Shanghai. While education quality and innovation activities have positive impacts, these are insufficient to fully offset the negative effects of the time factor.

By introducing previously under-explored control variables—such as total imports and exports, total fixed assets, housing area, and the number of healthcare institutions—this study bridges certain gaps in prior research and deepens the understanding of regional economic growth mechanisms. Controlling for time and regional differences enhances the explanatory power of the regional economic growth model. These improvements provide new perspectives on how education and innovation activities affect economic growth in Shanghai through understudied channels (Ren et al., 2024).

2. Literature review

2.1. Education, innovation, and economic growth

Since the concept of human capital was introduced in the 1950s, numerous studies have examined the contribution of education to economic growth. Schultz's seminal work in the United States demonstrated that between 1929 and 1957, education contributed 33% to economic growth (Schultz, 1961). In the 1970s, amid sluggish global economic growth, there was renewed interest in education as a driver of the economy (Schultz, 1990). Lucas (1988) further explored the impacts of human capital accumulation and education on economic development, highlighting the improvement of education quality as a key factor in promoting economic growth.

In China, education expenditure accounted for only 2.79% of GDP in 2004, far below the average of 5.1% found in developed countries (Fleisher and Zhao, 2010). Since 1999, the Chinese government has dramatically increased college and university enrollment, which saw an annual growth rate of 26.6% between 1999 and 2003. Studies have shown that education contributes 20.9% to China's economic growth, and for every 1% increase in tertiary enrollment, GDP increases by approximately 71.2 billion yuan (Li and Sun, 2023).

Innovation activities are also recognized as crucial for increasing productivity and promoting economic growth. Griliches (1998) emphasized the importance of determining innovation by analyzing patent statistics. Patents serve as an indicator of innovative output and technological advancement, which are essential for sustaining economic growth (Ulku, 2004).

2.2. Mediating role of international trade and fixed capital formation

Coe and Helpman (1995) studied international R&D spillovers and explored the impact of international trade as a mediating variable in economic growth. However, prior studies did not explicitly analyze the logarithm of total exports and imports as a specific variable influencing growth. Fagerberg (2018) highlighted that technological progress and structural change are key drivers of productivity growth and regional economic development, yet the specific mechanisms involving international trade remain under-explored.

Fixed capital formation represents investment in physical assets and infrastructure, which is fundamental for economic development. However, the complex effects of fixed capital formation on different economic indicators have not been thoroughly investigated, particularly in the context of Shanghai.

2.3. Control variables and their impact

When analyzing economic growth, previous studies have often overlooked control variables such as time factors, regional differences, total fixed assets, housing size, and the number of healthcare facilities (Xia et al., 2022). For instance, Papaevangelou et al. (2024) noted that while technological progress, R&D activities, and human capital had been discussed, the specific impacts of time and regional economic differences had not been thoroughly examined.

In Shanghai, variables such as total assets, housing size, and the number of medical institutions can significantly influence regional economic development, but this concept has not been adequately studied (Zhou et al., 2021). Manowaluilou et al. (2024) pointed out that neglecting these control variables limits the understanding of how various factors affect economic growth.

To address these gaps, this study introduces four new control variables:

1) Total imports and exports: Measuring the scale of international trade and its mediating effect on economic growth.
2) Total fixed assets: Reflecting the financial capacity and investment level in the region.
3) Housing area: Indicating the standard of living and potential impact on the labor market.
4) Number of healthcare institutions: Representing public health services that can affect labor productivity.

By controlling for time and regional differences, the study systematically analyzes the roles of these variables on economic growth in Shanghai over different periods. This approach enhances the explanatory power of the regional economic growth model and provides new insights into the mechanisms through which education quality and innovation activities affect economic growth.

The study is grounded in economic growth theory and innovation-driven theory. Higher education quality and technological innovation are posited to have direct positive impacts on economic growth. Improvements in the quality of higher education can directly increase labor productivity, thereby boosting economic growth (Lucas, 1988). Innovation activities contribute to productivity gains and economic expansion through the development and application of new technologies (Griliches, 1998).

In summary, while previous research has acknowledged the importance of education quality and innovation activities in promoting economic growth, there remains a lack of comprehensive analysis that includes specific mediating variables like international trade and fixed capital formation, as well as control variables such as time factors and regional differences. This study aims to bridge these gaps by introducing under-explored variables and systematically analyzing their impacts on Shanghai’s economic growth.

3. Research methodology and data sources

3.1. Model setup

This study adopts an empirical approach by utilizing panel data from Shanghai covering the period between 2014 and 2022 to construct a multiple regression model. The goal is to explore the effects of education quality, innovation activities, international trade, fixed capital formation, and the urbanization rate on economic growth. By categorizing variables into dependent, independent, mediator, and control variables, the model aims to identify the relationships and mechanisms between these factors (Joao, 2022). The specific variable definitions can be found in **Table 1**. To ensure robustness, the model controls for the impacts of time, region, and financial factors.

The basic form of the model is as follows:

$$\text{economic\_growth}_{it} = \beta_0 + \beta_1 \times \text{univ\_rnd}_{it} + \beta_2 \times \text{patent\_num}_{it}$$
$$+\beta_3 \times \log(imp_e xp_{it}) + \beta_4 \times \log(gfcf_{it}) + \beta_5 \times urban_r ate_{it} + \beta\_6 \tag{1}$$
$$\times (\text{year}_{it} + \text{region}_{it} + \text{assets\_billion}_{it} + \text{housing\_area\_10k\_sqm}_{it} + \text{medical\_establishments\_num}_{it}) + \epsilon_{it}$$

a) economic_growth_it: Economic growth variable (a measure of economic growth), which represents the economic growth situation in region *i* at time *t*. This variable is the dependent variable, i.e., the variable that the model attempts to explain or predict.

b) $\beta 0$: Constant term, representing the level of economic growth when all explanatory variables (independent variables) in the model are zero. This term captures the baseline level of economic growth that is not explained by other variables.

c) $\beta 1 \times$ univ_rnd_it: univ_rnd_it: University research and development (R&D) expenditure in region *i* at time *t*. This variable is used to measure educational quality and innovation capacity. β1: The coefficient of $univ\_rnd$ in relation to economic growth. If β1 is positive, it indicates that university R&D expenditure has a positive impact on economic growth; if negative, it indicates a negative impact.

d) $\beta 2 \times$ patent_num_it: patent_num_it: The number of patents in region *i* at time *t*. It is used to measure the output of innovation activities. β2: The coefficient of $patent\_num$ in relation to economic growth, reflecting the contribution of innovation activities to economic growth.

e) $\beta 3 \times$ log_imp_exp_it: The logarithm of the total imports and exports in region *i* at time *t*. This mediating variable reflects the impact of international trade on economic growth. β3: The coefficient of log_imp_exp in relation to economic growth, indicating the direct or indirect impacts of imports and exports on economic growth.

f) $\beta 4 \times$ log_gfcf_it: The logarithm of gross fixed capital formation in region *i* at time *t*. This mediating variable represents the level of investment.
β4: The coefficient of log_gfcf in relation to economic growth, indicating the contribution of fixed capital investment to economic growth.

g) $\beta 5 \times$ urban_rate_it: The urbanization rate in region *i* at time t. The level of urbanization is also an important factor influencing economic growth. β5: The coefficient of urban_rate in relation to economic growth, indicating the impact of urbanization on economic growth.

h) year_it: Time control variable, representing the year at time t, which controls for the impact of time on economic growth.

i) region_it: Regional control variable, representing region i, which controls for regional differences in economic growth.

j) assets_billion_it: Control variable for total assets, representing the total assets in region *i* at time t, controlling for the financial capacity of the region.

k) housing_area_10k_sqm_it: Control variable for housing area, representing the housing area in region *i* at time *t*, reflecting the living standards of the residents.

l) medical_establishments_num_it: Control variable for the number of medical establishments, representing the number of medical establishments in region *i* at time *t*, controlling for the impact of public health services on economic growth.

m) β6: The coefficient of the control variables in relation to economic growth, indicating how these variables affect economic growth when other factors are controlled.

n) ϵ_it:Residual term, representing the unexplained error or random disturbance in the model. This term captures all other factors not included in the model but which influence economic growth.

3.2. Variable definitions

Table 1. The sources and detailed information of the specific variables.

Variable Types	Variable Name	Variable Definitions
DV	tert_gdp	Proportion of GDP from the tertiary sector, reflecting economic structure and growth quality
DV	main_revenue_billion	Main business revenue (in billions of yuan), measuring economic output
DV	revenue_billion	Total revenue (in billions of yuan), indicating the overall scale of economic activity
DV	profits_billion	Total profit (in billions of yuan), representing economic profitability
DV	output_billion	Total output (in billions of yuan), reflecting the overall production level (Liang and Yang, 2019)
IV	univ_rnd	University R&D expenditure, measuring the quality of education and capacity for innovation. Higher university R&D spending indicates greater investment in research and innovation (Ulku, 2004)
IV	patent_num	Number of patents, representing the output of innovation activities and the technological innovation level of the region
Me	log_imp_exp	Logarithm of total imports and exports, serving as an intermediary variable for the effect of international trade on economic growth
Me	log_gfcf	Logarithm of gross fixed capital formation, reflecting investment levels and acting as an intermediary variable for the impact of investments on economic growth
Me	urban_rate	Urbanization rate, indicating the level of urban development and its influence on economic growth (Khan et al.)
CV	year	Year, controlling for the impact of time on economic growth.
CV	region	Region, controlling for regional economic disparities
CV	assets_billion	Total assets (in billions of yuan), controlling for financial capacity within regions
CV	housing_area_10k_sqm	Housing area (in 10,000 square meters), reflecting residents' living standards
CV	medical_establishments_num	Number of medical institutions, controlling for the impact of public healthcare services on economic growth (Acs et al., 2015)

3.3. Data sources

The data for this study were primarily obtained from the following sources:

- Economic data: The Shanghai Statistical Yearbook (2014–2022) and China Statistical Yearbook provide macroeconomic indicators such as GDP, revenue, profit, and total assets.
- Education and innovation data: Statistics on Higher Education, published by the Ministry of Education, and annual reports from the China National Intellectual

Property Administration provide data on university R&D expenditure and the number of patents.

- International trade and investment data: Import and export statistics from the General Administration of Customs and fixed asset investment data from the Statistical Yearbook of Fixed Assets Investment, published by the National Bureau of Statistics, provide information on trade volume and capital formation.
- Urbanization and social development data: Data on urbanization rates, housing area, and the number of medical institutions were collected from statistical publications produced by the National Bureau of Statistics and the Shanghai Municipal Government.

All the data were cleaned, standardized, and processed to ensure the accuracy and reliability of the analysis. For missing data, linear interpolation was employed to avoid biases in the model estimation caused by data incompleteness.

4. Analysis of the empirical process and results

Table 2 shows the correlations between several economic variables, reflecting the linear relationship between them. The following brief description outlines the results shown in the table and their validation. The correlations between tertiary GDP and tert_gdp and other variables are generally low. For example, the correlation coefficients with variables such as sales_billion_yuan, profit_billion_yuan and number of patents are very close to zero or even negative. This indicates that the linear relationship between tertiary industry GDP and these variables is very weak, with almost no significant linear correlation. According to **Table 3**, the correlation coefficient between Revenue from Main Business and Revenue_billion and Total Profit is 0.9399, which shows a very strong positive correlation. This indicates a strong linear relationship between the two, a result in line with common sense, i.e. usually the higher the turnover, the greater the profit. In terms of the relationships that total output has with the number of patents and university R&D expenditure, the correlation coefficients of (total output and billion output) with the number of patents and university R&D expenditure are 0.8239 and 0.8055, respectively, indicating a strong positive correlation between total output and innovative activities.

Table 2. Correlation matrix between economic variables.

Sample	tert_ gdp	Revenue_ billion	profits_ billion	output_ billion	Patent _num	Univ _rnd	log_ imp_exp	log_ gfcf	urban_ rate	urban_ rate
tert_gdp	1	-	-	-	-	-	-	-	-	-
revenue_billion	−0.0185	1	-	-	-	-	-	-	-	-
Profits_billion	−0.0574	0.9399	1	-	-	-	-	-	-	-
output_billion	0.0094	0.6535	0.5884	1	-	-	-	-	-	-
patent_num	−0.0448	0.891	0.8295	0.8239	1	-	-	-	-	-
univ_rnd	−0.0398	0.8646	0.7996	0.8055	0.8839	1	-	-	-	-
log_imp_exp	−0.0877	0.2901	0.3158	0.723	0.5505	0.49	1	1	-	-
log_gfcf	−0.0638	−0.312	−0.221	0.2277	−0.0169	−0.2	0.6267	0.6267	1	-
urban_rate	0.0446	0.0464	0.0695	0.0099	0.0283	0.02	−0.0083	−0.0083	−0.041	1

The correlation coefficient between the log of imports and exports and log_imp_exp with total output and output_billion is 0.723, indicating a moderate positive correlation, which may reflect the importance of foreign trade for output growth. The generally low correlation coefficients between the urbanization rate and the other variables suggest that the linear relationship between the urbanization rate and these economic indicators is not strong and may be influenced by other complex factors. The data revealed a clear positive correlation between some economic variables - such as income, profits and output - and innovative activities. However, the weak correlation between the urbanization rate and tertiary GDP, for example, as well as other economic indicators, may indicate a more complex relationship between urbanization rate and tertiary GDP. For a clearer picture of the correlations, see **Figure 1** below for the correlation matrix involving the economic variables.

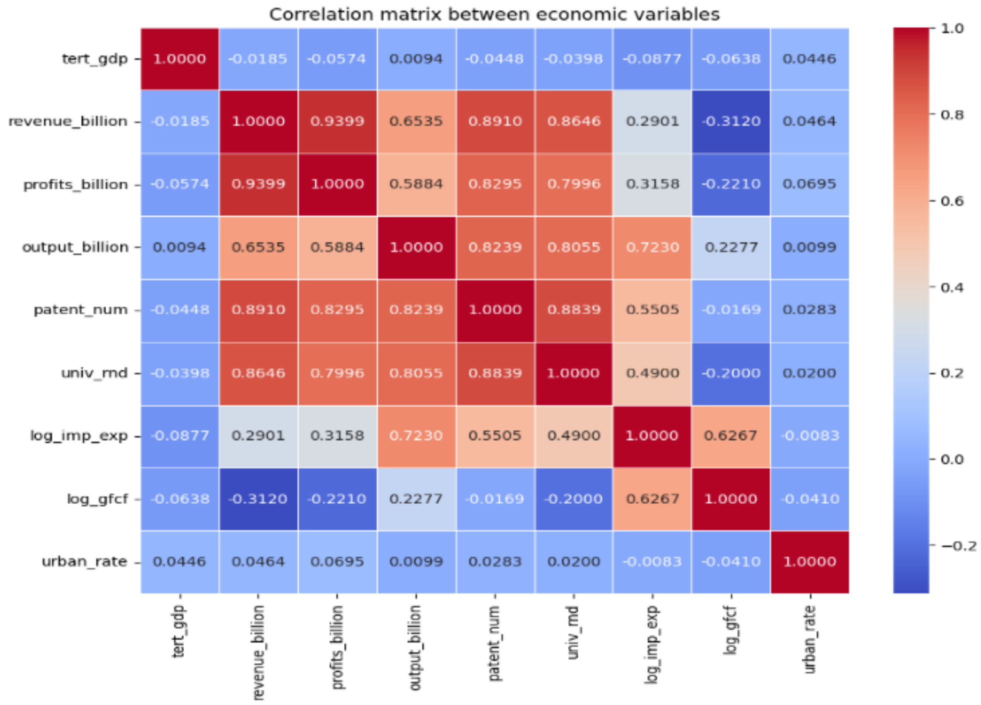

Figure 1. Correlation matrix of economic variables.

According to **Figure 1**, there are correlations between several economic variables, with correlation coefficients ranging from −1 to 1; negative correlations are shown in blue, while positive and strong correlations are shown in red. The correlation between tertiary GDP and most of the other variables is weak or negative, while the correlation between revenues and profits is very high, with a value of 0.9399. The correlation between output and the number of patents is 0.8239, and the correlation between the number of patents and R&D in universities is 0.8839, indicating that they are both significantly positively correlated. The logarithmic value of exports and imports and fixed capital formation is 0.6267, indicating a moderate positive correlation. The correlation between the urbanization rate and other variables is weak. A high correlation indicates a strong linear relationship, while a low correlation indicates a weak linear relationship.

Table 3. Analysis of variance for regression models.

Source	SS	df	MS
Model	9.78729265	1	9.78729265
Residual	30.286713	142	0.213286711
Total	40.0740056	143	0.280237801

According to **Table 3**, the number of observations equals 144. The *F*-statistic with 1 and 142 degrees of freedom equals 45.89. The *p*-value for the *F*-statistic is less than 0.0001. The *R*-squared equals 0.2442. The adjusted *R*-squared equals 0.2389. The root mean square error equals 0.46183. The model is based on 144 observations and the sample size is sufficient to provide robust regression results. The *F*-value of 45.89 corresponds to a *p*-value of 0.0000, which indicates that the independent variable has a highly significant effect on the dependent variable, so the hypothesis can be rejected at a significance level of 0.05. The *R*-squared shows that the model explains 24.42% of the total variance of the dependent variable. The adjusted *R*-squared is 23.89%, which is close to the *R*-squared, indicating that the independent variable can effectively explain the dependent variable. The root mean square error is 0.46183, indicating that the average deviation between the model's predicted and actual values is about 0.46. The ANOVA results show a statistically significant effect of the independent variable on the dependent variable, as well as a significant positive correlation between education and economic growth. The model shows that university R&D expenditure and univ_rnd, as a measure of the quality of education and innovation, have a significant positive impact. The *F*-statistic value of 45.89 and the *p*-value of 0.0000 show that investment in education has a significant effect on economic growth at a significance level of 0.05. This implies that as investment in education increases, economic growth also increases.

Table 4. Estimated regression coefficients.

Variable	Coefficient	Std. Err.	*t*	***P*** > |***t***|	[95% Conf. Interval]
univ_rnd	0.0010966	0.0001619	6.77	0.0	0.00078 to 0.001417
_cons	8.597788	0.0604397	142.25	0.0	8.47831 to 8.717266

Table 4 shows the effect of university research and development expenditure and univ_rnd on the dependent variable of economic growth, as well as its statistical significance in relation to the independent variables in the regression model. The regression coefficient for university R&D expenditure, univ_rnd, is 0.0010966. This means that all else being equal, for every unit increase in university R&D expenditure, there is a 0.0010966 unit increase in economic growth. Although this value may seem small, it reflects the positive contribution of investment in education to economic growth. The smaller standard error of 0.0001619 indicates that the estimates are more accurate and the data fluctuate less. The *t*-value of 6.77 indicates the extent to which the coefficients deviate from zero. The higher the *t*-value, the greater the contribution of the variables to the results of the model and the greater the impact of univ_rnd on economic growth. The *p*-value of 0.0 indicates that the results are statistically significant, much less than the commonly used significance level of 0.05. The

confidence interval suggests that the true regression coefficient may lie between 0.0007766 and 0.0014166 at the 95% confidence level. This range does not include zero, further validating the significance of the coefficients. The results of this regression model clearly indicate that university R&D expenditure has a significant positive impact on economic growth and that this impact is statistically significant.

Table 5. Results and interpretation of regression analyses of factors affecting economic growth.

Variable	**Coefficient**	**Std. Err.**	***t***	***P* > |*t*|**	**[95% Conf. Interval] Lower**	**[95% Conf. Interval] Upper**
Univ rnd	0.341663	0.148803	2.3	0.023	0.0470917	0.636234
Patent num	0.0688164	0.032053	2.15	0.034	0.0053637	0.132269
Year	−11.19835	4.041832	−2.77	0.006	−19.19956	−3.19714
Changning District	−311.3199	61.25613	−5.08	0	−432.5825	−190.057
Chongming County	−325.2668	103.0204	−3.16	0.002	−529.206	−121.328
Fengxian District	−220.2904	75.79352	−2.91	0.004	−370.3312	−70.2495
Hongkou District	83.34508	60.52218	1.38	0.171	−36.46463	203.1548
Huangpu District	−109.9484	73.67938	−1.49	0.138	−255.8041	35.90732
Jiading District	−368.2262	73.28469	−5.02	0	−513.3005	−223.151
Jing'an District	133.2377	67.06874	1.99	0.049	0.4684663	266.007
Jinshan District	−151.7426	81.28907	−1.87	0.064	−312.6624	9.177252
Minhang District	−775.3517	69.70519	−11.1	0	−913.3401	−637.363
Pudong New Area	−1150.004	153.592	−7.49	0	−1454.054	−845.953
Putuo District	−104.3475	52.85966	−1.97	0.051	−208.9885	0.293471
Qingpu District	−341.4122	79.60113	−4.29	0	−498.9906	−183.834
Songjiang District	−261.7704	53.2461	−4.92	0	−367.1764	−156.364
Xuhui District	185.405	67.83871	2.73	0.007	51.11149	319.6985
Yangpu District	4.066931	53.86118	0.08	0.94	−102.5567	110.6905
Assets billion	−0.032822	0.018811	−1.74	0.084	−0.070060	−0.00442
Housing area 10k sqm	0.0743521	0.008863	8.39	0	0.0568071	0.091897
Medical establishments num	1.398545	0.199941	6.99	0	1.002741	1.794349
Cons	22381.22	8112.19	2.76	0.007	6322.325	38440.11

In **Table 5**, a positive coefficient in each column indicates a positive correlation, a negative coefficient indicates a negative correlation, and the other variables remain unchanged. The standard errors of the coefficient estimates reflect the instability of the estimates. The *t*-statistic, obtained by dividing the coefficients by their standard errors, is used to test whether the coefficients are significantly different from zero. $p > |t|$, the *p*-value associated with the *t*-statistic, indicates the probability of observing the current data if the null hypothesis is true. The upper and lower bounds of the coefficient's 95% confidence interval indicate that we are 95% certain that the true value is within this range. The univ_rnd coefficient of 0.341663, $p > |t|$, and the test value of 0.023 indicate that university R&D expenditure has a significant positive effect on the dependent variable. Holding the other variables constant, for every unit increase in univ_rnd, the dependent variable is expected to increase by about 0.341663 units. The patent_num coefficient is 0.0688164, $p > |t|$, and the test value is 0.034, showing that the number of patents also has a significant positive effect on the dependent variable, which is expected to increase by. For every unit increase in patents in the dependent variable. The year coefficient is −11.19835, $p > |t|$, the value is 0.006, and the coefficient is negative, indicating that the dependent variable is expected to decrease over time by 11.19835 units for each additional year, and this effect is statistically significant.

The impacts of control variables such as assets, housing size, and the number of medical institutions on the dependent variable were also tested differently in different districts of Shanghai. For example, Changning District has a significant negative 311.3199 impact, while Xuhui District has a significant positive 185.405 impact.

The total assets values and the number of medical institutions as a response to the degree of economic growth and the degree of public services were measured and analyzed as follows:

a) Direct impact: Higher education quality (HEQ) and technological innovation (PAT) have a direct positive impact on economic growth. Improving the quality of higher education can directly increase the productivity of the labor force, thus boosting economic growth.
b) assets_billion, the coefficient of total assets is −0.032822, $P > |t|$, and the value is 0.084, so total assets has a slight negative effect on the dependent variable, but this is not significant at the 5% level of significance. housing_area_10k_sqm is the area of housing, with a coefficient of 0.0743521, $P > |t|$, and a value of 0.000, so the housing area has a significant positive effect on the dependent variable, indicating that a larger housing area is positively associated with higher economic growth.
c) medical_establishments_num is the number of medical establishments, with a coefficient value of 1.398545, $P > |t|$, and a value of 0.000, indicating that public health services have a positive effect on economic growth. The findings suggest that the quality of education, innovative activities, regional economic development, housing, and healthcare resources are the key factors driving economic growth, while the passage of time may bring some negative effects that inhibit economic growth. The performance of these factors varies in different areas of Shanghai.

According to **Table 6**, the ‘main revenue’ variable is defined as main_revenue_billion, and the urbanization rate is defined as urban_rate, with a coefficient of 1463.851 and a *p*-value of 0.793, which is statistically insignificant. This indicates that at the 95% confidence level, the urbanization rate has a statistically insignificant effect on the main_revenue_billion, and the effect of urbanization rate on main_revenue_billion is not significant. The wide confidence interval also indicates the high degree of uncertainty in this estimate. University R&D expenditure, defined as univ_rnd, has a statistically significant coefficient of 2.937846 and a *p*-value of 0.001. University R&D expenditure has a positive and significant impact on primary income. For every unit increase in university R&D expenditure, basic income increases by about $294 million. This supports the hypothesis that higher education activities contribute positively to economic growth. The ‘number of patents’ variable, defined as patent_num, has a statistically significant coefficient of 0.9300431, with a *p*-value of 0.000. The number of patents is significantly associated with an increase in primary income. The data show that for every unit increase in the number of patents, the basic income increases by $930 million, which indicates that innovative activities make a significant contribution to economic growth.

Table 6. Regression analysis of economic revenue determinants: Higher education and innovation metrics.

Dependent Variable	Independent Variable	Coefficient	Std. Err.	*t*	*P* > |*t*|	95% Conf. Interval
main revenue billion	urban rate	1463.851	5575.735	0.26	0.793	−9561.071, ..., 12488.77
main revenue billion	cons	8690.422	5242.218	1.66	0.1	−1675.035, ..., 19055.88
main revenue billion	univ rnd	2.937846	0.9016344	3.26	0.001	1.155041, ..., 4.720651
main revenue billion	patent num	0.930043	0.077998	11.9	0	0.7758173, ..., 1.084269
main revenue billion	log gfcf	−439.15	122.0744	−3.6	0	−680.5283, ..., −197.7718
revenue billion	urban rate	2690.611	5933.112	0.45	0.651	−9040.953, ..., 14422.17
revenue billion	cons	6683.761	5578.218	1.2	0.233	−4346.069, ..., 17713.59
revenue billion	univ rnd	0.242898	0.1079162	2.25	0.026	0.0295149, ..., 0.4562812
revenue billion	patent num	0.065171	0.0093356	6.98	0	0.046712, ..., 0.0836305
revenue billion	log gfcf	−17.5263	14.61104	−1.2	0.232	−46.41677, ..., 11.36413
profits billion	urban rate	680.7327	710.1315	0.96	0.339	−723.4128, ..., 2084.878
profits billion	cons	−49.6375	667.6544	−0.1	0.941	−1369.793, ..., 1270.518
profits billion	univ rnd	0.929868	0.1860783	5	0	0.5619348, ..., 1.297801
profits billion	patent num	0.057908	0.0160971	3.6	0	0.0260792, ..., 0.0897371
profits billion	log gfcf	62.00953	25.19359	2.46	0.015	12.19417, ..., 111.8249
output billion	urban rate	79.01333	1224.469	0.06	0.949	−2342.133, ..., 2500.16
output billion	cons	−2503.14	1151.226	−2.2	0.031	−4779.466, ..., −226.8181

The gross fixed capital formation variable, defined as log_gfcf, has a statistically significant coefficient of −439.15, with a *p*-value of 0.000. Gross fixed capital formation has a negative impact on primary income, and the data suggest potential inefficiencies in capital investment or an overemphasis on capital formation at the expense of other drivers of growth. The urbanization rate variable, defined as urban_rate, has a statistically insignificant coefficient of 2690.611, with a *p*-value of 0.651. Like the effect on primary income, the urbanization rate does not have a statistically significant effect on total income.

The university R&D expenditure variable, defined as univ_rnd, has a statistically significant coefficient of 0.2428981 and a *p*-value of 0.026. University R&D expenditure has a positive and significant impact on total income, albeit to a lesser extent than its effect on primary income. This suggests that tertiary education affects total income and that the impact of tertiary education on specific income streams may be more profound.

The ‘number of patents’ variable, defined as patent_num, has a statistically significant coefficient of 0.0651712 and a *p*-value of 0.000. The positive impact of patents on total income is reconfirmed, highlighting the importance of innovative activities.

The gross fixed capital formation (GFCF) variable, defined as log_gfcf, has a statistically insignificant coefficient of −17.52632 and a *p*-value of 0.232. The negative impact of GFCF on revenues is not significant, suggesting that its impact may be more complex.

For the analysis of profit and profit_billion, the coefficient of the urbanization rate (urban_rate) is 680.7327, with a *p*-value of 0.339, which is statistically insignificant. The effect of the urbanization rate on profit is not significant.

The coefficient of university R&D expenditure is 0.9298681, with a *p*-value of 0.000, which is statistically significant. University R&D expenditure has a significant positive impact on profitability, which is consistent with the view that higher education promotes innovation and thus directly increases profitability.

The coefficient of number of patents is 0.0579082, with a *p*-value of 0.000, which is statistically significant. The positive contribution of patents to profitability suggests that although patents are important, their direct effect on profitability may not be as pronounced as their effect on sales.

The coefficient of gross fixed capital formation is 62.00953, with a *p*-value of 0.015, which is statistically significant. Gross fixed capital formation has a positive impact on profitability, indicating that although GFCF may not significantly increase sales, it may contribute to profitability through efficient utilization of capital.

The analysis of the output variables and output aspects shows that the coefficient of the urbanization rate is 79.01333, with a *p*-value of 0.949, which is statistically insignificant. The interpretation is that urbanization rate has no significant effect on output, which is consistent with its effect on sales and profits.

The coefficient of the constant is −2503.142, with a *p*-value of 0.031, which is statistically significant. The negative constant indicates that other unobserved factors may have negative impacts on output, which requires further research.

These findings indicate that university R&D activities have significant positive impacts on primary income, total income, and profit, which highlights the important role of higher education in promoting economic growth. The number of patents also makes a significant positive contribution to economic outcomes, confirming the importance of innovative activities in driving economic growth. The urbanization rate does not have a significant impact on any of the economic outcomes, which may indicate that urbanization alone is not sufficient to drive economic growth and that other factors such as education and innovation are needed. Gross fixed capital formation had a mixed impact, with a negative effect on primary income but a positive one on profits, suggesting that the way capital is used may have different effects on different economic indicators. For a clearer demonstration of the correlations, the Python data are shown below in **Figure 2**.

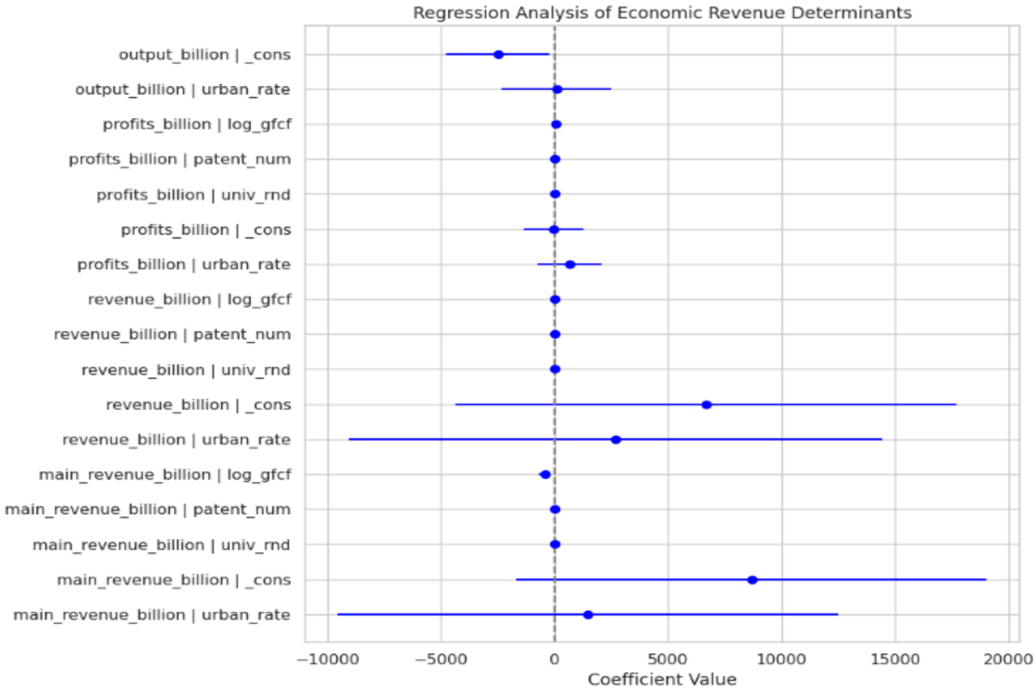

Figure 2. Visualizing the impact of key economic drivers on revenue, profits, and output.

Based on **Figure 2**, regression analyses show the complex determinants of economic income, helping us gain a deeper understanding of the multiple dimensions of and interactions between factors that affect economic growth. The figure shows that there are clear positive relationships between certain variables and economic indicators. For example:

a) profits_billion, urban_rate,main_revenue_billion, and urban_rate show that there are positive correlations between the urbanization rate and both profits and main revenue. This means that as the level of urbanization increases, there is a tendency for both profits and revenues to increase.

b) revenue_billion, log_gcfc, main_revenue_billion and log_gcfc also show that there are positive relationships between fixed asset formation and both revenues and primary incomes, suggesting that investment in fixed assets contributes to income growth in the economy.

Other variables in the graph show a negative relationship. For example, profits_billion and univ_rnd show a negative relationship between university R&D expenditure and profits, suggesting that in some cases, high R&D expenditure may have negative short-term impacts on profits. This could be because the nature of R&D activities is that they are rewarding in the long term.

From the variation of values shown in **Figure 2** and the results of the study, the effect of the urbanization rate on each economic outcome is mostly insignificant as its confidence interval crosses the zero line. This suggests that the urbanization rate may not have been a significant driver of economic growth in this study.

The impact of fixed capital formation shows some complexity. In main_revenue_billion, the regression coefficients are negative and significant, which may indicate inefficient investment or over-investment in capital. However, in profits_billion, the coefficient is positive and significant, suggesting that capital investment may still have a positive effect on profits under certain circumstances.

Finally, the constant term in output_billion is negative and significant, suggesting that other unobserved factors might negatively affect output. This finding highlights the need for further research on these unconsidered factors.

Based on **Table 6** and **Figure 3**, the set of visualizations enables a pairwise analysis of the relationship between four key variables: the role of higher education, the role of innovation in economic growth, international trade, and fixed asset formation. The purpose of this analysis is to explore the interactions between these factors and their potential impact on economic growth.

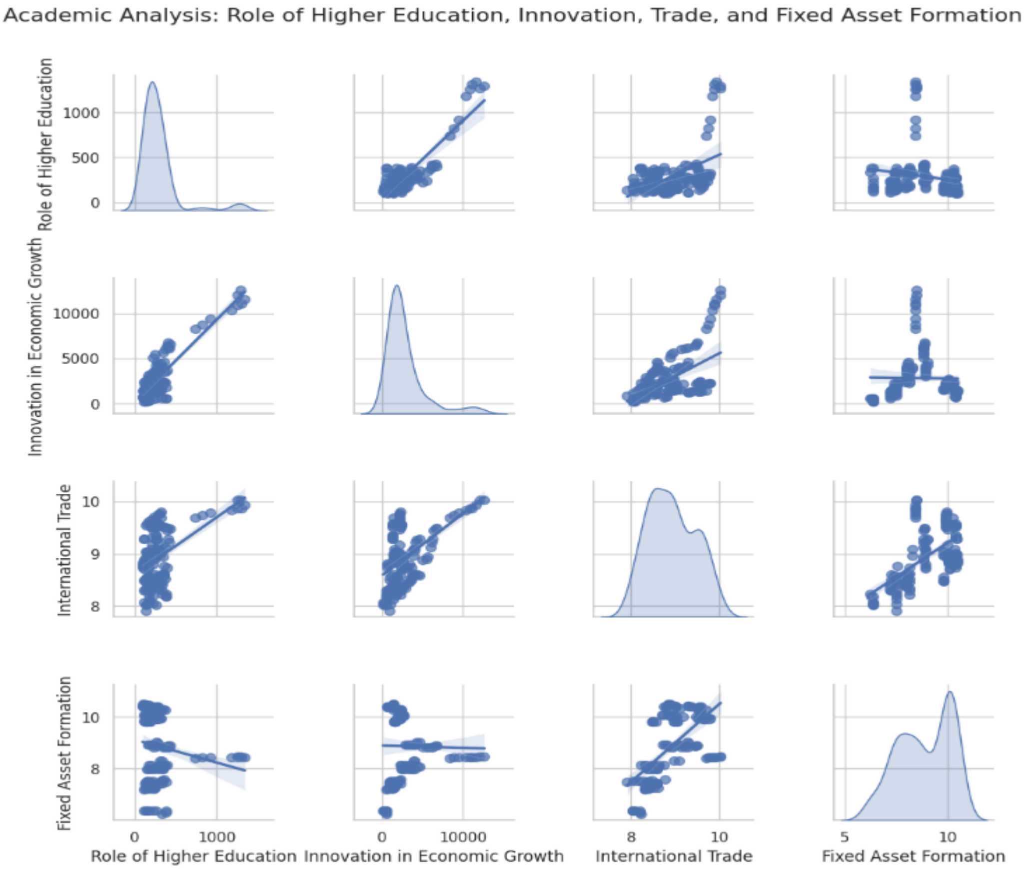

Figure 3. Exploring the interdependencies between higher education, innovation, international trade, and fixed asset formation: Implications for economic growth.

Higher education and university R&D expenditure measures and innovation, as measured by the number of patents, show a significant positive correlation. The scatter plot shows that regions with higher levels of investment in tertiary education typically generate more innovation. This finding emphasizes the key role of tertiary education in fostering innovative activity, which is itself an important engine of economic growth. There is also a positive correlation between higher education and international trade, but the correlation is relatively weak. While the scatter plot shows that regions investing more in tertiary education are more likely to participate in international trade, this relationship is less pronounced than the link between tertiary education and innovation.

Figure 3 shows that the correlation between tertiary education and fixed asset formation is weak or even slightly negative. This suggests that either regions focusing on education and R&D are not those with the highest levels of fixed asset investment or fixed asset investment in these regions is lagging behind the growth of investment in education and R&D.

Figure 3 shows that there is a significant positive correlation between innovation and international trade. Regions with more patents exhibit higher levels of international trade, suggesting that innovation activities play an important role in promoting regional trade. Innovation contributes not only directly to economic growth but also indirectly to the development of international trade.

Figure 3 shows that the correlation between innovation and fixed asset formation is relatively weak, suggesting that although innovation is crucial for economic growth, it is not directly associated with direct growth in fixed asset investment. The data suggest that the innovation-driven growth model relies more on the accumulation of intellectual capital than on traditional physical capital inputs. **Figure 3** shows that there is a moderate positive correlation between international trade and fixed asset formation, suggesting that regions participating more in international trade also typically have higher fixed asset investment, so international trade likely helps to drive capital formation and thus provides the necessary material base for sustained economic growth.

Finally, the results of the visualization in **Figure 3** were analyzed. This showed that higher education plays a crucial role in promoting innovation, which in turn becomes an important factor in driving international trade. Despite the positive impacts of these factors on economic growth, the link between them and fixed asset formation is not as strong as expected. The data shown in **Figure 3** suggest that education and innovation are more dependent on the accumulation of intellectual capital in promoting economic growth, whereas fixed asset formation requires a longer period or the influence of more external factors for its effects to become evident.

Findings (1) The important mediating role of international trade on economic growth.

The study shows that international trade activity, expressed as the logarithm of the total amount of exports and imports, log_imp_exp, plays an important role in mediating the relationship between the quality of education, as well as innovation activity and economic growth. While university R&D expenditure and the number of patents have direct positive effects on economic growth, these effects are further amplified when international trade is introduced as a mediating variable. International trade is not only a driver of economic growth, but it also enhances the impact of education and innovation on economic growth (Agyapong et al., 2017).

Findings (2) The impact of fixed capital formation on economic output has complexity.

The results of the study show the complexity of the impact of fixed capital formation and log_gfcf on different economic indicators. When analyzing primary income and main_revenue_billion, fixed capital formation shows a negative impact, suggesting that in some cases, too much capital investment leads to inefficient resource allocation or the neglect of other growth drivers. However, when analyzing profits, fixed capital formation shows a significant positive impact, suggesting that capital formation contributes to profitability through a more efficient use of capital.

Findings (3) The time factor has a significant negative impact on economic growth.

The coefficients of the time variable show a significant negative change in the economic growth variable and economic_growth_it for each additional year. This indicates that the challenges arising due to economic growth increased year by year during the study period because of changes in the external economic environment, policy uncertainty, and/or other unobserved factors. Despite the positive impacts of education and innovation activities on economic growth, these impacts do not fully offset the negative impacts of the time factor.

5. Conclusions and discussion

This study explores the impacts of education quality and innovation activities on economic growth, with particular attention paid to the intermediary roles of international trade and fixed capital formation. Through an analysis of panel data from 31 provinces and municipalities in China covering the period from 1999 to 2022, the following conclusions were drawn:

First, education quality and innovation activities have significant direct and indirect effects on economic growth. Improvements in higher education, reflected in increased university R&D expenditure, directly enhance workforce quality and productivity, thereby promoting economic growth. Additionally, an increase in the number of patents reflects active innovation, which drives technological progress and industrial upgrading.

Second, international trade plays a key intermediary role, significantly amplifying the positive effects of education and innovation on economic growth. Higher import and export volumes expand the market size and improve resource allocation efficiency, enabling the outcomes of education and innovation to be more broadly applied and disseminated, further promoting economic development.

Third, the impact of fixed capital formation on various economic indicators is complex. Excessive investment can lead to inefficient resource allocation, negatively affecting some economic indicators (e.g., initial revenue). However, in cases of moderate investment, fixed capital formation enhances the production capacity and has positive effects on profitability.

Finally, temporal factors negatively affect economic growth. Over time, increasing uncertainty in the economic environment, such as global economic fluctuations and policy adjustments, poses challenges to growth. Although education and innovation contribute positively to the economy, they cannot fully offset the negative effects of time.

In summary, this study verifies the hypotheses and identifies the mechanisms through which education quality, innovation activities, international trade, and fixed capital formation influence economic growth, providing new perspectives for understanding regional economic development drivers.

This study expands and deepens the existing literature and theories in several ways:

First, it addresses the research gap regarding the impact of import and export volumes. While previous studies have mentioned the influence of international trade on economic growth, they lacked detailed analysis of trade volume as a specific variable. By including the logarithmic value of trade volume in its model, this study explores how international trade acts as an intermediary, enhancing the positive effects of education quality and innovation on economic growth.

Second, this study improves the model by introducing key control variables, enhancing the reliability of the results. It incorporates total assets, housing area, and the number of medical institutions, systematically analyzing their impacts on economic growth across different time periods and regions. This approach addresses the shortcomings of prior studies that overlooked regional differences and temporal factors, thus increasing the explanatory power of the model.

Third, this study emphasizes the negative impact of temporal factors, revealing the dynamic characteristics of economic growth. By controlling for time, it demonstrates the significant adverse effects of temporal factors on economic growth, offering new evidence on the long-term challenges to economic development.

Furthermore, the study makes a methodological contribution by employing a multiple regression model with panel data analysis, providing more precise estimates of the relationships between variables. The inclusion of previously under-explored variables and intermediary mechanisms deepens the understanding of the complex relationships between education, innovation, and economic growth.

Finally, the findings provide empirical evidence for policy-making. They highlight the key factors driving economic growth, offering valuable insights that governments and decision-makers could utilize when formulating effective economic and education policies, thus contributing to sustainable economic development.

Based on the study’s findings, the following policy recommendations are proposed to promote sustainable economic growth:

- Increase investment in education and improve higher education quality: Governments should enhance the financial support available to universities, encouraging them to invest more in research and education, as well as cultivate highly skilled talent.
- Encourage innovation and strengthen intellectual property protection: Favorable policies should be introduced to motivate companies and research institutions to engage in innovation activities. Intellectual property protection mechanisms should be improved to ensure that innovation outcomes are effectively utilized and disseminated.
- Promote international trade and deepen openness: Trade policies should be optimized to reduce import and export barriers, and participation in global economic cooperation should be encouraged. Expanding the access to international markets can amplify the positive impacts of education and innovation on economic growth.
- Optimize the structure of fixed capital investment and improve investment efficiency: Efforts should be made to avoid over-investment and redundant construction, focusing instead on the quality and efficiency of investments. Capital should be directed toward high-yield and high-return areas to enhance investment efficiency.

- Strengthen economic risk management and enhance resilience: Long-term development strategies and contingency plans should be formulated to address the uncertainties posed by temporal factors. Improving the economy's ability to withstand external shocks is essential for sustainable growth.
- Improve social infrastructure and enhance public well-being: Investments in public services, such as housing and healthcare, should be increased to improve residents' quality of life. This will create favorable conditions for human capital development and support economic growth.

Although this study yields meaningful results, it has some limitations that future research should address:

- Geographic and temporal limitations: The data is primarily based on 31 provinces and municipalities in China, which may limit the generalizability of the findings to other countries or regions. Future studies could expand the scope to more countries and regions for comparative analysis.
- Limitations in data coverage: Due to data availability constraints, the study covers the period from 1999 to 2022, so longer-term trends and cyclical effects might not have been captured. Longer-term panel data could provide richer insights into the dynamics of economic growth.
- Limitations in variable selection: Although key variables were included, economic growth is influenced by many factors, such as policy environments, technological advancements, and international dynamics, which were not fully incorporated into the model. Future researchers could consider additional variables to refine the model further.
- Challenges in identifying causal relationships: This study primarily uses multiple regression analysis, which may not completely eliminate endogeneity or reverse causality issues. More advanced econometric methods, such as instrumental variable approaches or difference-in-differences models, could be employed in future research to strengthen the causal inferences.
- Data quality and availability issues: Some of the data may suffer from inconsistencies in statistical standards or missing values, which could affect the accuracy of the results. Improving the comprehensiveness and quality of the data used is crucial for enhancing the reliability of future research.
- Impacts of changes to the external environment: The study does not fully account for the effects of global economic fluctuations, pandemics, or other major events on economic growth, which could interfere with the findings. Future researchers could explore these factors more thoroughly.

By summarizing the findings, discussing the contributions, and providing policy recommendations, this study offers new perspectives on the impacts of education quality, innovation activities, international trade, and fixed capital formation on economic growth. Despite its limitations, it provides valuable insights for policy-makers and directions for future research.

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