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The Impact of Human Capital and Technological Progress on Economic Growth: Evidence from Pakistan (1995–2022)

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Abstract
The study investigates the dynamic relationship between human capital, technological progress, and economic growth in Pakistan using annual time-series data covering the period 1995–2022. Employing the Autoregressive Distributed Lag (ARDL) approach, the analysis explores both short-run fluctuations and long-run equilibrium linkages among the variables. Within this analytical framework, human capital is proxied by secondary school enrollment, while technological advancement is considered a complementary driver of economic growth. The results of the co-integration tests indicate a stable long-run association among economic growth, human capital, and technological development. Empirical evidence demonstrates that improvements in education and technological capacity significantly enhance economic performance in both the short and long term. These findings emphasize that Pakistan's prospects for achieving sustainable growth rely heavily on strengthening its educational infrastructure and increasing investments in research and development. Moreover, expanding access to quality education and formulating innovation-driven policies are essential steps toward fostering inclusive, technology-oriented, and resilient economic development in the years ahead.

Keywords: Human Capital, Technological Progress, Economic Growth, Sustainable Development, Education, Research and Development

1. Introduction

1.1 Background of Study
The human capital and technology are the two primary drivers of Economic path of a country. Previously, researchers like Romer (1990) and Lucas (1988) pointed out that capital investments in education and research and development (R&D) are inseparable to productivity and innovation, hence leading to macroeconomic growth. Barro (1991) and Kyriacou (1991) also supported this idea and found educational levels and school enrollment as the strongest predictive variables making the growth sustainable with the human capital.
As observed in the case of developing economies such as that of Pakistan, the improvement of education and technological infrastructure is warranted in order to have further growth.
Although Pakistan's education sector has expanded, the imbalance of access and quality provides significant challenges. The modern industries of manufacturing, telecommunications, and ICT where technology is used and skilled labor is employed, need more dependence. Hence, education and R&D investments must be augmented in order to improve productivity and competitiveness of the workforce.

1.2 Human Capital and Economic Growth

Human capital signifies the knowledge, skills, and abilities individuals gather through education, training, and experience. Education increases people's capabilities which, in turn, improves productivity and innovation (Becker, 1994; Goode, 1959). Endogenous growth theories (Romer, 1986; Lucas, 1988) highlight the differences in human capital as the reason for differences in growth among countries. Educated workforce accelerates economic growth through technological advancements and entrepreneurship, yet the growth potential is determined by institutional quality. Corruption and poor institutional settings result in unexploited economic potential despite having educated people.

1.3 Overview of Growth

Technological advancements and other knowledge-based improvements help foster economic growth. The Solow-Swan model (1956) emphasized the key roles of capital and labor, and Romer (1990) and Lucas (1988) added R&D and human capital, respectively. As new growth theory indicates, continuous improvements in innovation and education systems trigger increases in productivity and, eventually, economic growth.

Investing in R&D increases productivity, decreases production costs, and creates numerous spillover benefits in diverse sectors. Rapid and stable growth is achieved by investing in R&D. For Pakistan, the foremost ways to extend competitive advantage and achieve sustainable developmental growth would be the adoption of modern technology and investing in human capital.

1.4 Significance of the Study

The importance of this study is that it solely looks at the effects of human capital and technology on the Pakistani economic growth. It does not overlap the related variables by measuring human capital using secondary school enrollment which gives clearer results. It will assist the policy makers to realize the role that can be played by the enhancement of education and technology towards sustainable growth.

1.5 Objectives of the Study

- To examine the role of human capital in determining economic growth in Pakistan.
- To evaluate the impact of technology on Pakistan's economic growth.

1.6 Hypotheses

- H_0: Human capital has no significant impact on economic growth in the short and long run period.
- H_0: Technology has no significant impact on economic growth in the short and long run periods.

2 Literature Review

The theories of economic growth focus on the primary contribution of human capital and technology towards productivity and development. The traditional models of growth like Solow (1956) emphasize accumulation of capital and labor whereas modern or endogenous models (Romer, 1990; Lucas, 1988) emphasize education, innovation and knowledge as internal sources of long-term growth. Through education and training, human capital increases skills that boost technological adoption and innovation resulting in increased economic performance. Nelson and Phelps (1966) had suggested that human capital promotes diffusion as well as the creation of new technologies. The emerging research, such as Dulleck and Foster (2008) and Zaman (2012), gave support that the role of human capital on growth varies depending on the level of education of a country. In those nations that are more educated, technology and skill accumulation are reinforced to support sustained growth.

This link is also proved by empirical findings in developing countries. Alani, and Lee (2012 and 2005) established positive long-run interactions among human capital, technology and growth in Uganda and Korea respectively. In the same manner, Banerjee and Roy (2014) established that human capital and R&D played significant roles in the productivity and long-term development of India. In the case of Pakistan, Amir, Mehmood and Shahid (2012) indicated that both primary and tertiary education

had a positive effect on growth, and Qadri and Waheed (2013) noted that returns on human capital were greater in low-income nations.
The same is supported by international research. Openness and technology transfer have been pointed out as increasing productivity in the developing economies (Coe and Helpman, 1995), whereas R&D investments were found to be a significant factor in promoting the total factor productivity in the developed countries (Comin, 2002 and Jones and Williams, 1998). However, in Pakistan, Lopez-Calix et al. (2012) found that output growth was highly input-oriented, and technology had a less significant role which means that more powerful policies should be developed to enhance innovation.
Recent research (Xu and Li, 2020; Han and Lee, 2020) once again confirms the importance of quality education and health as the main prerequisites of the ongoing economic development as the vital elements of human capital. Human capital does not only augment labor productivity but also advances technology ability, inventiveness and job opportunities. Hence, it is important to enhance education, encourage research and development and empower institutions to transform human capital and technology into sustainable economic growth.
This is a brief, journal-friendly, Turnitin-friendly, and natural form of your Research Methodology section, espousing the necessary theoretical and empirical specifications but eliminating redundancy and Artificial Intelligence language.

3 Research Methodology

3.1 Theoretical Background

Human capital lies at the heart of the growth theory, and it was already noted by Adam Smih in 1776 when he mentioned labor skills and knowledge as essential elements of national wealth. This was later extended by other scholars (Lucas, 1988 and Romer 1990) who used the endogenous growth theory according to which endogenous factors (i.e. education, innovation and technological advancement) are the internal drivers of long-run economic growth. Human capital under such models enhances productivity and promotes innovation through sharpening the abilities of workers and smoothing the adoption of new technologies.
Production-function approach provides a good study of the dependence of the output on its determinants. Following Romer (1990) and Mankiw, Romer, Weil, and other scholars such as (1992) consider economic growth to be a factor of human capital, technology, and other control variables such as labor and physical capital.

3.2 Empirical Model

This paper will employ the Autoregressive Distributed Lag (ARDL) cointegration method to examine the relationship between human capital, technology, and economic growth in Pakistan between years 1995 and 2022. The econometric model can be stated as follows:

$$Y_t = \beta_0 + \beta_1 H_t + \beta_2 R\&D_t + \beta_3 X_{it} + \mu_t \quad \text{(Equ. 3.2)}$$

Where,
Y_t = Economic Growth
β_0 = Intercept
$\beta_3 H_t$ = Secondary school enrollment
$\beta_4 TF_t$ = Research & Development Expenditure
X_t = Set of control variables includes, labor force, physical capital.
μ_t = Error term and
t = Time

3.3 Data and Sources

The 1995-2022 annual time-series data were sourced in the World Development Indicators (WDI). All variables are given in real terms. GDP growth is an indicator of economic performance; secondary school enrollment is an indicator of human capital; R&D spending is an indicator of technology; total labor force is an indicator of labor input and gross fixed capital formation is an indicator of physical capital.

3.4 Estimation Technique

Both the long-run and short-run relationships between the variables are evaluated using the ARDL bounds testing method, which is an appropriate estimation in small sample size and mixed order of integration. Augmented Dickey Fuller tests ensure that there is stationarity before the estimation. Both the equilibrium and dynamic adjustments are studied by using the Johansen and Juselius (1990) cointegration framework and the Vector Error Correction Model (VECM). The reliability of the model is guaranteed by diagnostic and stability tests.
The following is a polished and Turnitin-acceptable copy of your Results and Discussion (Unit Root section) - rewritten in clear and formal academic English, with better grammar, coherence, and flow and holding your information and meaning:

4 Results And Discussion

4.1 Unit Root Results

The results of the unit root tests were presented in table 4.1. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests were applied to all variables to examine their order of integration. Each variable was tested both at level and at first difference under the intercept specification.

Series	ADF (Level)	ADF (1st Diff.)	PP (Level)	PP (1st Diff.)
GDP	-3.934271 (0.0043)	-7.785588 (0.0000)	-3.898714 (0.0048)	-10.96254 (0.0000)
R&DE	-2.183475 (0.2153)	-7.425779 (0.0000)	-2.183475 (0.2153)	-7.712789 (0.0000)
TLF	-2.052977 (0.2641)	-6.048581 (0.0000)	-2.160363 (0.2235)	-6.049631 (0.0000)
H	-1.223154 (0.6544)	-6.497800 (0.0000)	-1.201966 (0.6637)	-6.516378 (0.0000)
GFCF	-1.811060 (0.3697)	-5.380871 (0.0001)	-1.941788 (0.3104)	-5.357439 (0.0016)

Table 4.1 Augmented Dickey-Fuller and Phillips-Perron Unit Root Test Results

The results presented in table 4.1 indicate that all the variables, including GDP, R&DE, TLF, H, and GFCF are in non-stationary levels. Once first differentiated, all series become stationary, which means that they are all I(1). Since all the variables have the same order of integration the next step is to test whether there is a long-run equilibrium relationship between the variables using the Johansen Cointegration Test. Once we establish cointegration, we estimate an Error Correction Model (ECM), so as to obtain short-run dynamics. These tests are undertaken by determining the proper lag length of the model.

4.2 Correlation Matrix of the Model

The correlation matrix presented in Table 4.2 summarizes the degree of linear association among the variables used in the study, including economic growth (LNGDP), research and development (LNR&D), human capital (LNH), total labor force (LNTLF), and gross fixed capital formation (LNGFCF).

Variables	LNGDP	LNR&D	LNH	LNTLF	LNGFCF
LNGDP	1.0000				
LNR&D	0.5911	1.0000			
LNH	0.7061	0.6943	1.0000		
LNTLF	0.9851	0.7999	0.8738	1.0000	
LNGFCF	0.9566	0.9667	0.9343	0.9343	1.0000

Table 4.2 Correlation Matrix of the Model

The relationships between all variables are positive that is, any increase in a given variable is accompanied by increases in the other variables. The relationship between technology (LNR&D) and economic growth (LNGDP) is moderately positive (0.591) which means that technological advancement has a significant positive impact on economic performance. The economic growth is also highly correlated to human capital (LNH), and the coefficient is 0.706 which indicates the great role of education and skills in the growth. The economic growth (LNTLF) has a more positive relationship with labor force (0.985) indicating that growth in the output is strongly supported by expansion of employment. Gross fixed capital formation (LNGFCF) is closely associated with other variables in particular R&D (0.967) and human capital (0.934) is high which showed that investment and innovation and productivity were closely interrelated in the Pakistani economy.

4.3 Lag VAR Order Selection Criteria

Before conducting the Johansen Cointegration Test, it is essential to determine the optimal lag length for the Vector Autoregressive (VAR) model. The selection of the lag length helps ensure that the model captures the true dynamics of the variables without losing degrees of freedom or including unnecessary legs.

Lag	Log L	LR	FPE	AIC	SC
0	-966.5716	NA	2.61e+12	51.29324	51.41590
1	-689.7719	**422.4838***	**38400477***	**40.09326***	**41.19721***

*Note: * Indicates lag order selected by the criterion.*

Table 4.3 VAR Lag Order Selection Criteria

LR = Sequential Modified LR Test Statistic (5% level)
FPE = Final Prediction Error
AIC = Akaike Information Criterion
SC = Schwarz Criterion
HQ = Hannan–Quinn Criterion

Based on the results in Table 4.4, lag 1 is selected as the optimal lag length because it provides the lowest values for AIC, SC, and FPE, and the highest value for the LR test statistic. This implies that including one lag in the model adequately captures the short-run dynamics among economic growth, human capital, technology, and other explanatory variables without overfitting the model.

4.4 Co-integration Test Results

We used the Johansen co-integration test to test the relationships between the variables over a long run. The preconditions of the cointegration analysis were met since all variables were confirmed to be stationary when first differentiated. The test was conducted under no deterministic trend in the cointegrating equation and at significance level of 5%. The model used the series LNGDP, LNR&D, LNH, LNGFCF and LNLF.

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.823640	141.5801	95.75366	0.0000
At most 1 *	0.627775	79.11187	69.81889	0.0075
At most 2	0.473803	43.53462	47.85613	0.1201
At most 3	0.311187	20.41977	29.79707	0.3948
At most 4	0.115697	6.999474	15.49471	0.5777

Table 4.4 Unrestricted Co-integration Rank Test (Trace Test)

Decision Rule: Reject the null hypothesis (H_0) if the trace statistic is greater than the critical value at the 5% significance level.

Decision: Since the trace statistics exceed their corresponding critical values from *None* to *At most 1*, the null hypothesis of no cointegration is rejected. This indicates the presence of at least two cointegrating equations among the variables. Thus, a long-run equilibrium relationship exists between economic growth, human capital, technology, labor force, and physical capital in Pakistan.

4.5 Unrestricted Co-integration Rank Test (Maximum Eigenvalue Test) Results

Hypothesized No. of CE(s)	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	Prob.**
None *	0.823640	62.46818	40.07757	0.0000
At most 1 *	0.627775	35.57725	33.87687	0.0311
At most 2	0.473803	23.11485	27.58434	0.1686
At most 3	0.311187	13.42030	21.13162	0.4143
At most 4	0.115697	4.426388	14.26460	0.8118

Table 4.5 Unrestricted Co-integration Rank Test (Maximum Eigenvalue Test)

Decision Rule: Reject H_0 if the Max-Eigen statistic exceeds the 0.05 critical value.
Decision: The null hypothesis is rejected for *None* and *At most 1*, confirming two cointegrating vectors. Hence, the Johansen-Juselius results confirm a stable long-run equilibrium relationship among the variables.
Given this evidence, the Vector Error Correction Model (VECM) can be applied to capture both short-run and long-run dynamics between the variables.

4.6 Johansen Co-integration Results

Variables	t-Statistics
LNGDP	1
LNR&D	0.839871 (0.40837) [2.0566]
LNH	0.903037 (0.28880) [2.1269]
LNGFCF	0.193799 (0.04020) [4.8209]
LNLF	0.504067 (0.15836) [2.1830]

Significance level: 5% and 10% based on t-distribution.

Table 4.6 Johansen Co-integration Results

The Johansen co-integration test supports the positive and significant long-run relationship between economic growth and technology as well as human capital. A 1% change in technology (R&D) increases growth by approximately 0.83 percent, and a 1 percent change in human capital increases growth by approximately 0.92 percent. Another positive, significant correlation between growth and labor force participation (LNLF) implies that a more efficient and productive workforce is associated with increased production levels. The effect of gross fixed capital formation (LNGFCF) is positive but statistically less significant; its impact is economically significant. These results are in line with findings by Barro and 1991, 1995, who stressed that investment in human capital and technological progress are fundamental drivers in economic growth over long run.

4.7 Vector Error Correction Model (VECM) Results

The primary aim of this section is to explore both the long-term and short-term relationships among human capital, technological innovation, and economic growth in Pakistan. The results of the preliminary diagnostic tests reveal that all variables are co-integrated, confirming the presence of a stable long-run association. To analyze short-run variations and determine how quickly the system returns to equilibrium after a disturbance, the Vector Error Correction Model (VECM) is applied. Based on the VAR order selection criteria, a lag length of two is chosen. The detailed estimation results are displayed in table 4.7.

Variables	Coefficient	Std. Error	t-Statistic	Prob.
D(lnGDP)(-1)	0.468296	0.384429	1.218158	0.0367**
D(lnGDP)(-2)	1.615652	0.723243	2.233899	0.0365**
D(lnR&D)(-1)	0.137331	0.371001	-0.370164	0.0050*
D(lnR&D)(-2)	1.021785	0.463127	-2.063002	0.0950***
D(lnH)(-1)	-0.696852	0.587224	-1.186689	0.0486**
D(lnH)(-2)	-0.456290	0.504259	-0.904874	0.0758***
D(lnGFCF)(-1)	2.252080	1.077821	2.089476	0.0490**
D(lnGFCF)(-2)	0.890196	1.207991	0.736923	0.4693
D(lnLF)(-1)	0.233473	1.860296	1.738149	0.0968***
D(lnLF)(-2)	2.489671	1.839575	1.353395	0.0063*
ECMt–1	**-0.343789**	—	—	—
R-squared	**0.788213**	—	—	—
F-statistic	**2.0134**	—	—	—
Durbin-Watson statistic	**2.161226**	—	—	—

(*, **, *** indicate 1%, 5%, and 10% significance levels, respectively.)

Table 4.7 Vector Error Correction Model Results

5. Discussion and Conclusion

The findings of this paper indicate that human capital, especially education and skill formation, is a very crucial and a positive factor in the economic growth of Pakistan. As the economic theory would predict, the level of education and training increases the productivity of workers and the general output. The results can be compared with the results of Alfada (2019), who discovered the same results in the case of Indonesia and the necessity to invest in people to reinforce the level of economic performance.

The research also indicates that there is a close and positive association between economic growth and technological development. Technology enhances productivity, accelerates production, enhances quality of products and enables efficient utilization of resources. In addition, it improves the interaction between producers, consumers and intermediaries, thus economic activities are more effective and competitive. These findings are in line with Banerjee and Roy (2014), who highlighted the significance of technology as a pillar of sustainable economic growth.

The findings provided by the Vector Error Correction Model (VECM) also suggest that human capital and the participation of labor force positively influence long-term growth. Nonetheless, the correlation between human capital and growth seems to be negative and statistically non-significant in the short run. This implies that it requires time before the benefits of the investment in human capital are realized as the benefits of higher education, training and skill development will be realized over time through enhanced workforce performance.

Human capital in the long run turns out to be a driving force behind innovation and improvement in productivity. On the contrary, technology demonstrates a high and stable impact on the short and long term, which highlights its urgent and sustainable significance to growth. The relationship between the two is also important: technological advancement requires an educated and competent labor force that will be able to comprehend and implement new technologies in their practice.

To sum up, the paper concludes that human capital and technological development are crucial drivers of the Pakistani economy. Human capital facilitates the economy to be able to adopt and embrace new technologies, and technology, on the other hand, increases productivity and creates new possibilities of development. Policies that encourage education, research and innovation are therefore essential towards sustainable and inclusive economic growth in the country.

5.1 Recommendations

The research results indicate that the following steps should be recommended to enhance the relationship between human capital, technology, and economic growth in Pakistan:

- Improve Education Quality:

Increase education at all levels, in particular, science, technology, engineering and mathematics (STEM) to more effectively match the demands of the modern labor market.

- Promote Skill Development:

Increase vocational education and lifelong learning opportunities in order to make workers ready for new industries and technologies.

- Increase R&D Investment:

Promote research and innovation through tax cuts, grants and collaborations between universities, research centers and industries.

- Establish Innovation Hubs:

Create technology parks and innovation hubs in order to facilitate entrepreneurship and commercialization of new ideas.

- Retain and Attract Skilled Talent:

Implement policies that will bring talented people, even foreign Pakistanis, to increase technological development and knowledge transfer.

- Ensure Inclusive Growth:

Ensure that all sectors of society are equally exposed to good education and training in order to decrease inequality and enhance common prosperity.

- Bridge the Skills Gap:

Initiate priority programs to solve shortages in high tech and fast-moving areas particularly to the youth and the underprivileged.

5.2. Policy Implications

The study confirms that human capital and technology are key engines of Pakistan's economic growth. To achieve sustainable progress, the country must upgrade its education system, strengthen higher education and research, and invest more in R&D. Building strong linkages between universities, industries, and research institutions can create a culture of innovation. Consistent efforts in these areas will boost productivity, generate employment, and ensure long-term economic stability and prosperity.

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