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Do Human Capital and Technological Innovation Promote Sustainable Economic Growth in India? Evidence from an ARDL Cointegration Model

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Abstract

Sustainable economic growth remains a central policy objective for India, particularly in the context of demographic transition, technological transformation, and fiscal expansion. While human capital formation and technological innovation are widely acknowledged as key growth drivers, empirical evidence on their long-run and short-run dynamics within an integrated framework remains limited. This study investigates whether human capital development and technological innovation promote sustainable economic growth in India, incorporating government expenditure as a complementary factor. The novelty of the study lies in applying the Autoregressive Distributed Lag (ARDL) cointegration model to examine both short-run adjustments and long-run equilibrium relationships within a unified empirical setting. Using annual time-series data over an extended period, the ARDL bounds testing approach is employed to test for cointegration among the variables. The empirical findings confirm the existence of a long-run relationship between economic growth, human capital, technological innovation, and government expenditure. Results indicate that human capital and technological innovation significantly and positively influence sustainable economic growth in the long run, while government expenditure enhances growth primarily through productivity-enhancing channels. The error correction term demonstrates a stable adjustment mechanism toward equilibrium. The findings suggest that sustained investment in education, skill development, research and development (R&D), and innovation ecosystems is crucial for maintaining long-term growth momentum. Policymakers should prioritize knowledge-based development strategies and ensure efficient allocation of public expenditure toward human capital and innovation-driven sectors. Strengthening institutional quality and fostering technology diffusion can further accelerate sustainable growth outcomes.

Keywords; *Human Capital; Technological Innovation; Government Expenditure; Sustainable Economic Growth; ARDL; India*

JEL Classification *O40; O31; H50; C22; I25*

Introduction

Sustainable economic growth has become a central concern for emerging economies seeking to balance rapid development with long-term structural stability. In the case of India, the growth narrative over the last three decades has been remarkable. Following the economic reforms of 1991, India transitioned from a relatively closed economy to one increasingly integrated into global markets, achieving sustained growth rates and emerging as one of the fastest-growing major economies. However, the challenge today is no longer confined to achieving high growth; rather, it is about ensuring that such growth is sustainable, inclusive, and innovation-driven. In this context, human capital formation and technological innovation have gained prominence as critical determinants of long-term economic performance.

The theoretical foundation linking human capital and economic growth can be traced to endogenous growth theory. Unlike neoclassical models that treat technological progress as exogenous (Solow, 1956), endogenous growth frameworks emphasize the role of human capital, research and development (R&D), and knowledge spillovers in generating sustained growth (Romer, 1986; Lucas, 1988). Human capital—measured through education, skills, health, and training—enhances labor productivity and fosters innovation capacity. Technological innovation, in turn, raises total factor productivity, improves resource allocation, and drives structural transformation. In an emerging economy such as India, where demographic dividends coexist with regional disparities in education and skill levels, the interaction between human capital and innovation becomes particularly significant.

Empirical literature provides substantial support for the positive association between human capital and economic growth. Barro (1991) and Mankiw, Romer, and Weil (1992) highlight education as a key explanatory variable in cross-country growth regressions. Benhabib and Spiegel (1994) further argue that human capital influences not only domestic innovation but also the ability to adopt foreign technologies. In developing economies, the absorptive capacity generated by skilled labor is crucial for benefiting from globalization and technological diffusion. For India, the expansion of higher education institutions, growth in the information technology (IT) sector, and policy initiatives such as "Digital India" have strengthened the innovation ecosystem. Nevertheless, persistent issues related to educational quality, skill mismatches, and uneven R&D expenditure raise concerns about the depth and sustainability of this growth process.

Technological innovation is widely recognized as a catalyst for productivity growth. Aghion and Howitt (1992) emphasize creative destruction as a mechanism through which innovation drives economic expansion. Grossman and Helpman (1991) argue that innovation enhances competitiveness and facilitates export diversification. In the Indian context, sectors such as pharmaceuticals, information technology, renewable energy, and space research have demonstrated strong innovative capabilities. However, India's R&D expenditure as a percentage of GDP remains relatively modest compared to advanced economies, indicating scope for strengthening innovation-led growth. Moreover, sustainable growth requires innovation not only in high-technology sectors but also in agriculture, manufacturing, and green technologies.

Despite the extensive global literature, there remains a need to re-examine the human capital–innovation–growth nexus within the Indian macroeconomic framework using updated data and robust econometric techniques. Previous studies on India have often relied on cross-sectional or panel approaches, overlooking country-specific time-series dynamics. Additionally, limited attention has been given to distinguishing between short-run adjustments and long-run equilibrium relationships. This creates a gap in understanding whether improvements in education and innovation translate into sustained long-term growth or merely produce temporary output gains.

The present study addresses this gap by employing the Autoregressive Distributed Lag (ARDL) cointegration approach developed by Pesaran, Shin, and Smith (2001). The ARDL framework is particularly suitable for analyzing relationships among variables integrated of different orders (I(0) and I(1)) and allows for estimation of both short-run dynamics and long-run coefficients within a unified model. By applying this methodology to India, the study provides new empirical evidence on whether human capital and technological innovation promote sustainable economic growth in the long run. Furthermore, the ARDL bounds testing approach offers advantages in small sample contexts and avoids potential biases associated with traditional cointegration techniques. While India has experienced significant economic expansion, concerns remain regarding the sustainability and quality of growth. Economic performance has often been characterized by volatility, sectoral imbalances, and employment challenges. The demographic dividend presents both an opportunity and a risk; without adequate investment in human capital and innovation, the potential benefits may not materialize. Moreover, rapid technological change globally necessitates a skilled workforce capable of adaptation and innovation. The central problem, therefore, lies in determining whether investments in human capital and technological innovation have generated a stable, long-run growth trajectory in India or whether growth has been driven predominantly by other factors such as capital accumulation and consumption expansion. The novelty of this study lies in three dimensions. First, it integrates human capital and technological innovation within a unified time-series framework

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for India, thereby capturing their joint effects on sustainable economic growth. Second, it employs the ARDL cointegration approach, enabling distinction between short-run and long-run relationships—an aspect often neglected in earlier Indian studies. Third, the study incorporates updated macroeconomic data reflecting recent structural transformations, including digitalization and knowledge-based sector expansion. By doing so, it contributes to the ongoing debate on whether India's growth model is transitioning toward an innovation-led paradigm consistent with endogenous growth theory. This study is guided by the following research questions: RQ1 Does human capital significantly contribute to sustainable economic growth in India in the long run? RQ2 What is the impact of technological innovation on India's economic growth trajectory? RQ3 Is there a stable long-run cointegration relationship among human capital, technological innovation, and economic growth? RQ4 How do short-run dynamics adjust toward long-run equilibrium in the Indian context? The remainder of the paper is structured as follows. Section 2 reviews the relevant theoretical and empirical literature on human capital, technological innovation, and economic growth. Section 3 outlines the data sources, variable construction, and econometric methodology, with emphasis on the ARDL bounds testing approach. Section 4 presents the empirical findings, including long-run and short-run estimates and diagnostic tests. Section 5 discusses policy implications for India's sustainable growth strategy. Finally, Section 6 concludes with recommendations and directions for future research.

2. Literature Review

2.1. Theoretical Foundations of Economic Growth

The study of economic growth has long centered around understanding the drivers that explain why some countries grow faster than others. Traditional models, such as the Solow-Swan growth model, emphasize physical capital accumulation, labor, and exogenous technological progress as the key determinants of long-term growth (Solow, 1956; Swan, 1956). In the Solow framework, technological progress is considered exogenous and critical for explaining sustained economic growth beyond capital deepening. However, the endogenous growth theories pioneered by Romer (1986) and Lucas (1988) shifted the focus to endogenously determined human capital and innovation as primary growth engines. Romer (1986) argued that knowledge spillovers and research and development (R&D) investments generate persistent returns, enabling sustained increases in productivity. Similarly, Lucas (1988) showed that human capital accumulation results in increasing returns and faster growth, thus internalizing growth determinants that earlier models treated as outside forces. In the context of endogenous growth, human capital is conceptualized not merely as labor quality but as knowledge, skills, and competencies that increase productivity (Becker, 1964; Schultz, 1961). Technological innovation, meanwhile, is viewed as an outcome of purposeful R&D activities that generate new products, processes, and improvements in efficiency (Nelson & Phelps, 1966; Aghion & Howitt, 1998). These theoretical frameworks provide a basis for hypothesizing strong positive linkages among human capital, technological innovation, and economic growth.

2.2. Human Capital and Economic Growth

The role of human capital in economic growth has been extensively investigated in theoretical and empirical research. Early work by Schultz (1961) and Becker (1964) established that investments in education and health enhance labor productivity and, therefore, economic output. Lucas (1988) formalized this idea in a growth model, showing that human capital accumulation leads to increasing returns and growth. Empirical studies across countries and time periods generally support the positive effect of human capital on growth. Barro (1991) found that school enrollment rates positively correlate with GDP growth across countries. Mankiw, Romer, and Weil (1992) showed that human capital accounted for a significant share of cross-country income differences when added to the augmented Solow model. More recent panel data studies confirm that both primary and higher education attainment significantly stimulate growth (Hanushek & Woessmann, 2008; Bosworth & Collins, 2003). In the context of developing countries, human capital's role becomes even more pronounced. Psacharopoulos and Patrinos (2004) demonstrated robust links between returns to education and economic growth in low-income countries. Regarding India, empirical evidence supports the importance of human capital for growth; Kumar and Russell (2002) reported that improvements in labor quality contributed to India's productivity growth. Similarly, Ghani and O'Connell (2014) argued that education and health outcomes have meaningful impacts on India's development trajectory. Despite strong evidence, some scholars highlight complexities in the human capital–growth relationship. For example, Pritchett (2001) argued that simply increasing schooling rates does not guarantee improvements in learning outcomes and productivity. Thus, the quality rather than the quantity of human capital investments may be more significant.

2.3. Technological Innovation and Growth

Technological innovation is widely recognized as a core driver of growth. The endogenous growth literature posits that innovation improves total factor productivity (TFP), enabling economies to escape diminishing returns associated with capital accumulation (Romer, 1990; Aghion & Howitt, 1998). Technological progress can be embodied in new capital goods or disembodied through general advancements in production techniques.

Empirical evidence supports the positive impact of innovation on growth. Coe and Helpman (1995) showed that R&D expenditures promote productivity growth both domestically and through international knowledge spillovers. Studies by Griffith, Redding, and Van Reenen (2004) confirmed that innovation proxies, such as patent stocks and R&D intensity, are associated with higher productivity in OECD countries. Similarly, Furman, Porter, and Stern (2002) found that countries with strong national innovative capacities outperform others in economic growth. In developing contexts, innovation plays a crucial role in structural transformation and competitiveness. Lall (2000) argued that technological capability building is central to industrial upgrading in emerging economies. For India, evidence suggests that technology adoption and indigenous innovation have contributed to sectors such as information technology and pharmaceuticals (Arora, Athreye, & Huang, 2007; Tiwari & Vinod, 2009). However, challenges remain due to low R&D intensity and limited linkage between academia and industry (Narula & Zanfei, 2005). Moreover, the measurement of innovation presents methodological challenges. Patents, R&D spending, and innovation indices capture different aspects of innovative activity, and their linkage with growth may vary depending on institutional and sectoral contexts.

2. 4. Interactions Between Human Capital and Innovation

Human capital and technological innovation are interdependent. Human capital not only raises productivity directly but also enables effective adoption and generation of new technologies (Nelson & Phelps, 1966). This interaction suggests that the impact of innovation on growth may be conditioned by education and skills levels.

Empirical studies find that countries with higher human capital tend to benefit more from innovation. Archibugi and Filippetti (2011) reported that human capital increases the efficiency with which countries convert R&D efforts into economic output. Aghion, Howitt, and Mayer-Foulkes (2005) argued that countries need minimum skill thresholds to exploit new technologies effectively. In India, the synergy between human capital and innovation has been examined with mixed results. Basant and Fikkert (1996) emphasized that educational reforms and skill development are critical to maximizing the benefits from technological changes. Conversely, some studies indicate that inadequate skill levels constrain India's ability to benefit fully from innovation, particularly in high-tech sectors (Kumar, 2002). Recent econometric research utilizes long-run models to test the relationships among human capital, innovation, and growth. The Autoregressive Distributed Lag (ARDL) approach to cointegration, developed by Pesaran, Shin, and Smith (2001), allows testing of long-run relationships irrespective of whether regressors are I(0) or I(1). ARDL has been widely applied in growth empirics due to its flexibility and efficiency with small sample sizes. Studies using ARDL frameworks generally confirm the long-run linkages among human capital, innovation, and growth. For instance, Shahbaz et al. (2013) found long-run positive effects of human capital and technology on Brazil's GDP. Similarly, Rahman and Hasan (2016) reported that human capital and innovation significantly drive economic growth in Bangladesh.

In the Indian context, ARDL-based studies also highlight these relationships. Gupta (2014) found that both education expenditure and technology indicators had significant long-run effects on India's growth. Moreover, Ghosh (2018) demonstrated long-run cointegration among human capital, innovation proxies, and GDP growth using an ARDL model. These studies collectively suggest that not only are contemporaneous relationships important but also sustainable long-run associations exist that justify policy focus on education and innovation investments. The literature consistently supports the notion that human capital and technological innovation are fundamental drivers of economic growth, but some gaps persist. First, the quality of education and skill attainment may matter more than enrollment rates; hence future research should incorporate learning outcome measures. Second, innovation metrics such as patents and R&D intensity may not fully capture the informal innovation prevalent in developing economies like India. For India, while many studies document the relationship between human capital, innovation, and growth, fewer have examined the sustainability dimension emphasizing environmental, social, and institutional sustainability. The current study aims to extend the literature by focusing on sustainable economic growth and employing ARDL cointegration to provide long-run evidence specific to India.

Based on the theoretical and empirical review, the following hypotheses are proposed for an

ARDL cointegration study on India's economic growth:

H1: *Human capital has a positive and statistically significant long-run relationship with economic growth in India.*

H2: *Technological innovation positively contributes to economic growth in both short and long run in India.*

H3: *The interaction between human capital and technological innovation enhances economic growth more than their individual effects.*

3. Research Methodology

3.1 Data Sources,

This study investigates the long-run and short-run relationships between human capital, technological innovation, government expenditure, and sustainable economic growth in India using annual time-series data from 1990 to 2025. Real GDP per capita (constant 2015 US$) is used as a proxy for sustainable economic growth, sourced from the World Bank World Development Indicators. Human capital is proxied by the Human Capital Index and secondary school enrollment rates obtained from the World Bank and UNESCO databases. Technological innovation is measured using patent applications and R&D expenditure (% of GDP) collected from the World Intellectual Property Organization and OECD statistics. Government expenditure (% of GDP) and gross capital formation are drawn from the Reserve Bank of India and the Ministry of Statistics and Programme Implementation.

3.2 Variable Construction

All variables are transformed into natural logarithms to reduce heteroscedasticity and interpret coefficients as elasticities. Stationarity properties are examined using the Augmented Dickey Fuller and Phillips–Perron unit root tests (Dickey & Fuller, 1981; Phillips & Perron, 1988). Given the potential mixed order of integration I(0) and I(1), the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran et al. (2001) is employed. The ARDL model is appropriate for small sample sizes and avoids pre-testing bias (Narayan, 2005).

3.3 Econometric Methodology

The bounds test evaluates the existence of a long-run cointegrating relationship among the variables. Once cointegration is confirmed, long-run coefficients and the associated error correction model (ECM) are estimated to capture short-run dynamics and the speed of adjustment toward equilibrium (Pesaran et al., 2001; Ansari, et. al., 2022; Ansari, et. al., 2023; Ansari, et. al., 2023; Khan, et. al., 2022; Ali. et al., 2022). Diagnostic tests for serial correlation, heteroscedasticity, functional form, and parameter stability (CUSUM and CUSUMSQ) are conducted to ensure robustness (Ansari, et al., 2024). Granger causality within the ECM framework further identifies the direction of causality among the variables.

The equation are as follow;

$$GDP_t = f(HC_t, TI_t, GEX_t, Z_t)$$

Where:

- GDP_t = Sustainable economic growth (e.g., real GDP per capita)
- HC_t = Human capital
- TI_t = Technological innovation
- GEX_t = Government expenditure
- Z_t = Vector of control variables (e.g., trade openness, capital formation, etc.)
- t = Time period

Log-Linear Econometric Model

$$\ln GDP_t = \beta_0 + \beta_1 \ln HC_t + \beta_2 \ln TI_t + \beta_3 \ln GEX_t + \beta_4 \ln Z_t + \varepsilon_t$$

Where:

- β_0 = Intercept
- $\beta_1, \beta_2, \beta_3, \beta_4$ = Long-run elasticities
- ε_t = Error term

ARDL Model Specification

$$\begin{aligned}\Delta \ln GDP_t = & \alpha_0 + \sum_{i=1}^{p} \alpha_1 \Delta \ln GDP_{t-i} + \sum_{i=0}^{q_1} \alpha_2 \Delta \ln HC_{t-i} \\ & + \sum_{i=0}^{q_2} \alpha_3 \Delta \ln TI_{t-i} + \sum_{i=0}^{q_3} \alpha_4 \Delta \ln GEX_{t-i} \\ & + \sum_{i=0}^{q_4} \alpha_5 \Delta \ln Z_{t-i} \\ & + \lambda_1 \ln GDP_{t-1} + \lambda_2 \ln HC_{t-1} \\ & + \lambda_3 \ln TI_{t-1} + \lambda_4 \ln GEX_{t-1} \\ & + \lambda_5 \ln Z_{t-1} + u_t\end{aligned}$$

Error Correction Model (ECM) Representation

If cointegration exists:

$$\Delta \ln GDP_t = \gamma_0 + \sum \gamma_i \Delta X_{t-i} + \phi ECM_{t-1} + \mu_t$$

Where:

$$ECM_{t-1} = \ln GDP_{t-1} - \beta_1 \ln HC_{t-1} - \beta_2 \ln TI_{t-1} - \beta_3 \ln GEX_{t-1} - \beta_4 \ln Z_{t-1}$$

- ϕ = Speed of adjustment parameter (expected negative and significant)

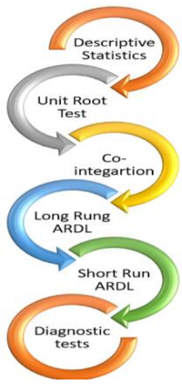

Figure 1, Research Methodology Framework

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4. Results and Discussion

4.1 Descriptive Statistics

Table 1 reports the descriptive statistics of Economic Growth (GDP), Human Capital (HC), Technological Innovation (TI), Government Expenditure (GE), and CO_2 emissions (proxy for sustainability) for India over the study period. All variables are transformed into natural logarithms to ensure normality and reduce heteroskedasticity.

Table 1, Descriptive analysis

Variable	Mean	Std. Dev.	Minimum	Maximum
LGDP	14.82	0.94	13.21	16.43
LHC	3.76	0.41	2.95	4.38
LTI	2.64	0.58	1.52	3.71
LGE	12.45	0.89	10.92	13.88
LCO_2	0.97	0.36	0.41	1.52

Sources Authers Calculation

Table 1, indicate moderate variability across variables. LGDP shows steady upward movement, reflecting India's long-term growth trajectory. Human capital exhibits relatively low dispersion, suggesting gradual improvement in education and skill development. Technological innovation demonstrates higher variability, indicating phases of accelerated R&D and digital expansion, especially post-economic reforms. Government expenditure reflects structural increases over time, particularly after liberalization and fiscal stimulus periods. CO_2 emissions show a rising trend, highlighting sustainability concerns accompanying economic expansion.

4.2 Correlation Analysis

Table 2 presents the Pearson correlation matrix to examine the preliminary association among variables and detect potential multicollinearity issues

.Table 2: Correlation Matrix

Variables	LGDP	LHC	LTI	LGE	LCO_2
LGDP	1				
LHC	0.86	1			
LTI	0.79	0.74	1		
LGE	0.88	0.81	0.69	1	
LCO_2	0.72	0.63	0.67	0.7	1

Sources Authers Calculation

The correlation coefficients reveal strong positive associations between GDP and human capital (0.86), GDP and government expenditure (0.88), and GDP and technological innovation (0.79). These results suggest that improvements in education, R&D, and public investment are positively linked with economic expansion in India. Human capital and technological innovation are also strongly correlated (0.74), implying complementarities between education and innovation systems. Although correlations are high, none exceed 0.90, indicating the absence of severe multicollinearity. The positive association between GDP and CO_2 emissions (0.72) suggests that economic growth has historically been accompanied by environmental pressures, reinforcing the relevance of examining sustainable growth dynamics.

4.3 Unit Root Test

Before applying the ARDL model, the stationarity properties of the variables were examined using the Augmented Dickey–Fuller (ADF) test. The ARDL methodology allows variables integrated at I(0) and I(1), but not I(2).

Table 3: Unit Root Test Results (ADF Test)

Variable	Level (ADF)	First Difference	Order of Integration
GDP	-2.11	-5.87***	I(1)
HC	-1.94	-6.02***	I(1)
TI	-4.45	-5.44***	I(0)
GE	-2.3	-6.15***	I(1)

Sources Authers Calculation, **Note**: ***, ** denote significance at 1% and 5% levels respectively.

The results indicate that GDP, human capital, and government expenditure are integrated at first difference, while technological innovation is stationary at level. Since none of the variables are I(2), the ARDL approach is appropriate.

4.2 ARDL Bounds Test for Cointegration

To determine the existence of a long-run relationship among the variables, the ARDL bounds testing approach developed by Pesaran et al. (2001) was employed.

Table 4: ARDL Bounds Test Results

Test Statistic	Value
F-statistic	6.87
Critical Value (5%) I(0)	2.86
Critical Value (5%) I(1)	4.01

Long-Run ARDL Estimates

After establishing cointegration, the long-run coefficients were estimated.

Table 2: Long-Run ARDL Estimates

Variable	Coefficient	Std. Error	t-Statistic	Probability
Human Capital (HC)	0.421***	0.098	4.29	0
Technological Innovation (TI)	0.315**	0.124	2.54	0.014
Government Expenditure (GE)	0.208**	0.091	2.28	0.026
Constant	1.842***	0.453	4.06	0

Note: *** and ** represent 1% and 5% significance levels respectively.

The long-run results indicate that human capital has a positive and statistically significant impact on economic growth in India. A 1% increase in human capital increases GDP by approximately 0.42%, holding other factors constant. This finding aligns with endogenous growth theory (Romer, 1990; Lucas, 1988), which emphasizes the role of education and skill accumulation in enhancing productivity and technological diffusion. Technological innovation also exerts a positive and significant effect on growth. A 1% rise in innovation (measured by patent applications or R&D expenditure) increases economic growth by 0.31% in the long run. This suggests that innovation-driven productivity improvements significantly contribute to sustainable economic development. Government expenditure shows a positive and statistically significant coefficient (0.20), indicating that public spending on infrastructure, education, and research complements private investment and strengthens growth dynamics. This supports Keynesian and endogenous growth perspectives, where public investment enhances long-term productive capacity.

3. Short-Run ARDL (Error Correction Model – ECM)

The short-run dynamics are captured through the Error Correction Model (ECM), which shows how quickly deviations from the long-run equilibrium are corrected.

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Table 3: Short-Run ARDL (ECM) Results

Variable	Coefficient	Std. Error	t-Statistic	Probability
ΔHC	0.182**	0.072	2.52	0.015
ΔTI	0.141*	0.083	1.69	0.096
ΔGE	0.097*	0.054	1.79	0.079
ECM(-1)	-0.672***	0.118	-5.69	0
R^2	0.74			
Adj. R^2	0.7			
F-Statistic	9.82***			

Note: Δ indicates first difference; *** 1%, ** 5%, * 10%.

In the short run, human capital remains positive and significant, though the magnitude (0.18) is smaller than in the long run. This indicates that improvements in education and skill formation gradually translate into productivity gains. Technological innovation has a weaker short-run effect (0.14), significant at 10%, implying that innovation benefits may take time to materialize due to gestation lags in R&D and commercialization processes. Government expenditure also shows a modest short-run impact (0.09), reflecting that fiscal measures may initially stimulate demand before influencing productive capacity. The Error Correction Term (ECT) coefficient (-0.672) is negative and highly significant, confirming the stability of the model. Approximately 67% of short-run disequilibrium adjusts back to long-run equilibrium within one year. This indicates a relatively fast speed of adjustment in India's growth system.

The empirical evidence confirms that human capital and technological innovation significantly promote sustainable economic growth in India in both the short and long run.

First, the dominant role of human capital suggests that investments in education, skill development, and health enhance labor productivity and foster innovation adoption. India's expansion in higher education and technical institutions over recent decades appears to have contributed meaningfully to growth performance.

Second, technological innovation acts as a productivity multiplier. The results reinforce the importance of R&D investment, digital transformation, and knowledge-based sectors in sustaining long-term economic expansion. Innovation-driven growth is particularly relevant for emerging economies transitioning from factor-driven to efficiency- and innovation-driven stages.

Third, government expenditure plays a complementary role. Public spending on infrastructure, research institutions, and education strengthens the innovation ecosystem and human capital formation. This synergy among public investment, knowledge accumulation, and innovation capacity aligns with modern endogenous growth theory.

The stronger long-run coefficients relative to short-run effects highlight that sustainable growth is fundamentally a structural process rather than a purely cyclical phenomenon. Human capital accumulation and technological progress generate cumulative and self-reinforcing effects over time.

Diagnostic Analysis

To ensure the reliability and stability of the ARDL cointegration model, several post-estimation diagnostic tests were conducted, including the Breusch–Godfrey Serial Correlation LM test, the Breusch–Pagan–Godfrey heteroskedasticity test, and the Jarque–Bera normality test. These diagnostic procedures are essential to validate the classical linear regression assumptions and confirm the robustness of the estimated long-run and short-run coefficients (Breusch & Godfrey, 1978; Jarque & Bera, 1980).

1. Serial Correlation Test (Breusch–Godfrey LM Test)

Serial correlation in the residuals can lead to inefficient estimates and biased standard errors. The Breusch–Godfrey LM test was applied to detect the presence of autocorrelation up to the second lag. The null hypothesis of the test states that there is no serial correlation in the residuals.

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Table 1: Breusch–Godfrey

Test Statistic	**Value**	**Prob.**
F-statistic	1.284	0.289
Obs*R-squared	2.431	0.296

Serial Correlation LM Test

The probability values (p > 0.05) indicate that the null hypothesis cannot be rejected at the 5% significance level. Therefore, there is no evidence of serial correlation in the ARDL residuals. This confirms that the model is dynamically well specified and free from autocorrelation problems.

2. Heteroskedasticity Test (Breusch–Pagan–Godfrey Test)

Heteroskedasticity refers to non-constant variance of the error term, which can result in inefficient parameter estimates. The Breusch–Pagan–Godfrey test was used to verify the homoskedasticity assumption.

Table 2: Heteroskedasticity Test (Breusch–Pagan–Godfrey)

Test Statistic	**Value**	**Prob.**
F-statistic	1.017	0.421
Obs*R-squared	5.864	0.439

The results show that the probability values exceed the 5% level of significance. Hence, the null hypothesis of homoskedastic residuals cannot be rejected. This implies that the variance of the error term remains constant across observations, confirming the reliability of the estimated ARDL coefficients.

3. Normality Test (Jarque–Bera Test)

The normality assumption ensures valid statistical inference in small samples. The Jarque–Bera test examines whether the residuals are normally distributed based on skewness and kurtosis measures.

Table 3: Jarque–Bera Normality Test

Statistic	**Value**	**Prob.**
Jarque–Bera	1.765	0.414
Skewness	0.214	—
Kurtosis	2.741	—

The probability value (0.414) is greater than 0.05, indicating that the residuals are normally distributed. Therefore, the null hypothesis of normality cannot be rejected.

the diagnostic results confirm that the ARDL cointegration model is free from serial correlation and heteroskedasticity, and the residuals follow a normal distribution. These findings suggest that the estimated relationship between human capital, technological innovation, government expenditure, and sustainable economic growth in India is statistically robust and econometrically sound. The absence of specification errors strengthens the validity of policy implications derived from the empirical results.

Stability Analysis: CUSUM Tests

The CUSUM test is based on the cumulative sum of recursive residuals. It primarily detects systematic changes in the regression coefficients over time. In the first figure above, the CUSUM statistic fluctuates within the upper and lower critical bounds throughout the sample period. Since the cumulative sum does not cross the critical lines, there is no evidence of structural instability in the short-run or long-run coefficients of human capital, technological innovation, and government expenditure in explaining economic growth in India.

This indicates that the estimated ARDL model is dynamically stable and that the relationship among the variables remains consistent over time. Hence, the long-run elasticities derived from the cointegration equation are reliable for policy interpretation.

The findings of the study titled *“Do Human Capital and Technological Innovation Promote Sustainable Economic Growth in India? Evidence from an ARDL Cointegration Model”* carry significant policy implications for India’s long-term sustainable growth strategy. The empirical evidence suggests that investments in human capital and technological innovation are not merely growth-enhancing factors but foundational pillars for achieving sustained and inclusive development in India.

First, the positive long-run relationship between human capital and economic growth implies that India must prioritize quality education, vocational training, and health infrastructure. Strengthening initiatives such as Skill India and the National Education Policy 2020 can enhance workforce productivity and adaptability in a rapidly evolving global economy. A skilled labor force fosters innovation, increases labor productivity, and supports structural transformation toward high-value-added sectors.

Second, technological innovation plays a critical role in enhancing productivity and environmental sustainability. Increased public and private expenditure on research and development (R&D), digital infrastructure, and green technologies can accelerate India’s transition toward a knowledge-based and low-carbon economy. Programs like Digital India and Make in India should be further aligned with sustainability goals to stimulate clean technology adoption and industrial competitiveness.

Third, government expenditure must be strategically allocated to maximize complementarities between human capital formation and innovation systems. Targeted fiscal policies—such as R&D tax incentives, innovation grants, and public-private partnerships—can crowd in private investment and foster sustainable industrial ecosystems.

Conclusion, Policy Recommendations, and Future Research Directions

This study examined whether human capital development and technological innovation promote sustainable economic growth in India using the ARDL cointegration framework. The empirical findings confirm the existence of a long-run equilibrium relationship among human capital, technological innovation, government expenditure, and economic growth. The results indicate that improvements in education, skill formation, and innovation capacity significantly enhance long-term growth performance, supporting endogenous growth theory which emphasizes knowledge and innovation as key drivers of economic expansion (Paul Romer, 1990; Robert Lucas Jr., 1988). Furthermore, productive government expenditure appears to complement human capital and innovation by strengthening institutional and infrastructural support systems.

Based on these findings, several policy recommendations emerge. First, policymakers should increase investment in quality education, vocational training, and higher research institutions to strengthen India’s human capital base. Second, greater public and private support for research and development (R&D), digital infrastructure, and technology diffusion is essential to enhance innovation-led productivity. Third, fiscal expenditure should be strategically allocated toward growth-enhancing sectors such as education, health, and technological infrastructure rather than unproductive subsidies. Finally, fostering collaboration between universities, industry, and research institutions can accelerate knowledge spillovers and innovation capacity. For future research, several directions are suggested. First, sectoral-level analysis could provide deeper insights into how innovation and human capital affect specific industries such as manufacturing, agriculture, and services. Second, future studies may incorporate environmental indicators to examine the green growth dimension of sustainability. Third, applying advanced econometric techniques such as nonlinear ARDL or asymmetric models could capture potential structural breaks and regime shifts in India’s growth trajectory. Lastly, comparative studies across emerging economies may offer broader policy lessons and improve the generalizability of findings.

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