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Human Development and Technological Progress in Türkiye: New Evidence from Multiple Structural Breaks

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Abstract: *This study examines the long-run relationship between human development and technological progress in Türkiye over the period 1990–2023. Technological progress is proxied by patent counts, while human development, trade openness, and economic policy uncertainty are included as explanatory variables. To account for possible regime changes in the Turkish economy, the analysis employs advanced time-series techniques that allow for structural breaks. First, the Zivot–Andrews unit root test is used to determine the order of integration under endogenous breaks. Second, the Maki cointegration test is applied to investigate long-run relationships in the presence of multiple structural breaks. Finally, long-run coefficients are estimated by the fully modified ordinary least squares (FMOLS), the dynamic ordinary least square (DOLS), and the canonical cointegration regression (CCR) estimators. The findings reveal that human development has a positive and statistically significant effect on technological progress in Türkiye. Trade openness also supports patent production, whereas economic policy uncertainty weakens it. Overall, the results suggest that technological progress depends not only on economic incentives but also on broader human development conditions and macroeconomic stability.*

Keywords: Human Development, Technological Progress, Time-series Analysis, Türkiye

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1. Introduction

Technological progress is widely regarded as one of the main determinants of sustainable economic growth, international competitiveness, and structural transformation in production. In an era in which the knowledge economy has become increasingly prominent, countries' capacity to generate innovation depends not only on research and development (R&D) expenditures or industrial infrastructure, but also on broader development indicators such as the quality of human capital, the level of education, health conditions, and institutional structure (Awode & Oduola, 2025; Fan & Jackson, 2025). In this context, technological progress should not be viewed merely as a technical or sector-specific phenomenon; rather, it reflects a multidimensional structure that embodies social welfare, human capacity, and the overall quality of development. Therefore, examining the relationship between human development and technological progress constitutes an important field of inquiry in both development economics and innovation economics (Tunsi & Alidrisi, 2023).

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The concept of human development is based on a broader understanding of development that emphasizes improving individuals not only in terms of income, but also in terms of education, health, and quality of life (Nguyen, 2025). From this perspective, human development can be regarded as a fundamental factor that enhances productivity, supports knowledge creation, and strengthens the social foundation of innovation activities. Societies with higher levels of education, better health conditions, and longer life expectancy are expected to have a greater capacity to generate new knowledge, adopt existing technologies, and adapt them to domestic production processes (Ranis, 2011). For this reason, it is theoretically reasonable to expect that improvements in human development will support technological progress, either directly or indirectly.

However, the relationship between human development and technological progress does not emerge with the same intensity across all countries (Lechman, 2009). The strength of this relationship may vary depending on complementary factors such as economic structure, institutional quality, international trade, financial development, and international capital flows (Nguea, 2025). In some countries, improvements in human capital and educational capacity are translated more rapidly into innovation capacity, whereas in others the same effect remains more limited because of institutional weaknesses, low absorptive capacity, financial constraints, dependence on imported technology, or a weak R&D ecosystem (Correa et al., 2010; Radosevic, 2019; World Bank, 2008). This makes it necessary to examine empirically the effect of human development on technological progress.

The literature includes various studies examining the links between human development and innovation, human capital, economic growth, economic complexity, and environmental technology indicators. However, a substantial part of the existing research either adopts a panel data approach based on large groups of countries (Akar et al., 2021; Atılgan & Kütükçü, 2025; Torun et al., 2009) or evaluates technological progress through indirect proxies such as innovation, information and communication technology investments, green patents, or economic complexity rather than through direct measures of technological advancement (Akyazı & Korkmaz, 2024; Bucak, 2021; Torun et al., 2009). Studies focusing on Türkiye, by contrast, mainly concentrate on human capital, innovation, and growth (Eygü & Coşkun, 2020), the importance of technology for human development (Kabaklarlı & Konya, 2021), human capital and development indicators (Çalışkan, 2010; Emirkadı, 2020), or the dynamics of the components of the human development index (Şahin & Gökdemir, 2016). In this context, it can be argued that studies directly examining how human development affects technological progress, and how this relationship evolves in the case of Türkiye from a time-series perspective, remain limited. Therefore, analysing this relationship directly in the context of technological progress for a developing economy such as Türkiye has the potential to make an original contribution to the literature.

This study empirically examines the relationship between human development and technological progress in the case of Türkiye, using patent counts as an indicator of technological progress. The use of a patent-based measure makes it possible to assess innovation capacity through a concrete, observable, and measurable output. At the same time, trade openness, and economic policy uncertainty as explanatory variables allows technological progress to be analyzed in connection with human development as well as with broader macroeconomic factors such as economic performance, openness, and policy stability. In this respect, the study treats technological progress as a multidimensional process shaped by development dynamics and macroeconomic conditions, rather than merely as the outcome of innovation in a narrow sense. Advanced time-series econometric methods are employed in order to capture the long-run relationships among the variables in the presence of structural breaks. The findings indicate that technology policies should extend beyond R&D incentives and be designed together with areas that support human development, such as education, health, and broader development conditions. In this sense, the study has the potential to offer important policy implications for Türkiye and for developing countries with similar structural characteristics, suggesting that technological progress should be supported through broader development strategies that strengthen human development and macroeconomic stability.

The remainder of the study is organized as follows. Section 2 presents the theoretical background, literature review, and the development of the research hypotheses. Section 3 describes the dataset and the empirical model. Section 4 outlines the econometric methodology employed in the analysis. Section 5 reports and discusses the empirical findings. Section 6 provides a broader discussion by evaluating the implications and significance of the findings for the Turkish economy. Finally, section 7 concludes the study.

2. Theoretical Framework and Literature Review

2.1. Theoretical Framework

Human development and technological progress are theoretically linked through the channels of productivity, knowledge creation, and absorptive capacity. Improvements in education, health, and living standards enhance individuals' capabilities, raise labour productivity, and strengthen the ability of societies to generate, adopt, and adapt new technologies. A more educated and healthier population is expected to contribute more effectively to innovation processes, research activities, and the diffusion of technological knowledge across sectors. In this sense, human development provides a supportive foundation for technological progress by improving both the quality of human capital and the efficiency with which knowledge is transformed into productive outcomes (Awode & Oduola, 2025; Nguyen, 2025; Ranis, 2011).

At the same time, the impact of human development on technological progress is not necessarily automatic, since it may depend on complementary structural conditions such as institutional quality, economic openness, and macroeconomic performance. Even when human development improves, weak institutions, limited absorptive capacity, financial constraints, or an underdeveloped innovation ecosystem may reduce the extent to which these gains are translated into technological outputs. Therefore, the relationship between human development and technological progress should be understood as a multidimensional process in which social capabilities interact with broader economic and institutional structures. This perspective suggests that improvements in human development are expected to promote technological progress, particularly when supported by favorable structural conditions (Correa et al., 2010; Fan & Jackson, 2025; Nguea, 2025).

2.2. Literature Review

The relationship between human development and technological progress has been examined through different empirical settings, methodological approaches, variable selections, data periods, and country groups. In literature on Türkiye, earlier studies mainly focused on the human capital and development dimensions rather than directly modelling technological progress. Çalışkan (2010) examined human capital expenditures and human development in Türkiye through education and health indicators and argued that inadequacies in these areas negatively affect human development indicators. Similarly, Emirkadı (2020) evaluated Türkiye's development process and human capital performance through education, health, and population indicators and emphasized that strengthening human capital is critical for Türkiye's development performance. Although these studies provide an important conceptual basis for linking human development with long-term development outcomes, they do not directly examine whether improvements in human development are transformed into measurable technological outputs.

A second group of Turkish studies focuses on the relationship between human development, economic growth, human capital, and innovation. Şahin and Gökdemir (2016) examined the short- and long-run dynamics of the components of the human development index in Türkiye over the period 1981–2013 and found that income per capita and tertiary school enrollment positively affect life expectancy, whereas primary and secondary school enrollment do not have statistically significant effects. Eygü and Coşkun (2020), covering the 1995–2018 period, examined the relationship among human capital, innovation, and economic growth in Türkiye and found that human capital and innovation support economic growth in the long run. They also reported a one-way causality running from human capital to innovation. Compared with earlier descriptive studies, these works provide stronger econometric evidence on the development–growth–innovation nexus in Türkiye. However, their main focus is economic growth or human capital rather than patent-based technological progress as the dependent variable.

A third strand of the literature incorporates technology-related indicators more directly, although the direction of analysis and the selected proxies differ from the present study. Kabaklarlı and Konya (2021) examined the importance of technological development and R&D activities for human development in Türkiye and argued that technology supports human development through improvements in education, health, and income. Akyazı and Korkmaz (2024), focusing on Türkiye over the period 1990–2018, examined the relationship between the green economy and the human development index. Their findings indicated the existence of a long-run relationship among the variables and showed bidirectional causality between green patents and the human development index. Bucak (2021), using panel data for the EU15 countries and Türkiye over the period 1995–2014, examined the relationship among economic complexity, human development, and carbon emissions. The results showed that human development causes economic complexity and that both human development and economic complexity affect carbon emissions. These studies are relevant because they employ technology-related indicators such as R&D, green patents, and economic complexity. Nevertheless, they either examine the effect of technology on human development, focus on environmental or complexity-based indicators, or use panel data structures rather than a Türkiye-specific time-series model of patent-based technological progress.

The international literature provides broader evidence by using different country groups, data periods, methods, and technology proxies. Torun et al. (2009) examined OECD countries and found that innovation and information and communication technology investments positively affect the human development index. Lechman (2009) analyzed the relationship between technological progress and economic development, especially through ICT indicators, and reported a strong positive relationship between technological development and human/economic development, with this effect being more pronounced in less developed countries. Ranis (2011) examined the relationship between technology and human development and their contribution to economic growth. The findings emphasized that human development and technological progress positively affect growth, while trade openness, R&D, and domestic patents reinforce technological change. Akar et al. (2021), using panel data for 25 transition economies over the period 2002–2018, examined the effect of human development on economic growth through two models. Their findings showed that human development positively and significantly affects economic growth, whereas unemployment has a negative effect. Atılgan and Kütükçü (2025), focusing on MIKTA countries over the period 1998–2022, examined the effects of human development and economic complexity on economic growth. Their results indicated that human development positively and significantly affects economic growth, while the effect of economic complexity is statistically insignificant. These studies demonstrate that human development is closely related to growth and technology-related outcomes; however, most of them rely on cross-country or panel settings and do not focus specifically on Türkiye’s patent-based technological progress.

More recent international studies have extended the literature by incorporating digitalization, financial globalization, economic complexity, uncertainty, and industrial performance. Tunsi and Alidrisi (2023) developed an innovation-based human development index for G8 countries and showed that countries’ human development rankings change significantly when technological and innovation dimensions are incorporated. Nguyen (2025), using a panel VAR approach for ASEAN-6 countries over the period 2002–2021, found that financial globalization supports human development both directly and indirectly through technological innovation. Mohammedi et al. (2025), covering developed and developing countries over the period 1990–2022, examined the effect of the digital economy on sustainable development by considering geopolitical risks. Their findings showed that the digital economy positively affects both environmental performance and human development, whereas geopolitical risks weaken sustainable development. Nguea (2025), using system GMM for 27 African countries over the period 2000–2017, found that ICT, measured by mobile phone and internet penetration, improves human development and that trade openness, financial development, electricity consumption, and democracy strengthen this effect. Oliveira et al. (2025), using panel data for 18 countries over the period 2009–2019, examined the relationship among technological progress, human capital, energy consumption, political uncertainty, and economic growth. Their findings showed that human capital, particularly intermediate education, supports economic growth, whereas political uncertainty negatively affects growth. Awode and Oduola (2025), focusing on 36 African countries over the period 1996–2021, found that human capital positively affects industrial productivity and competitiveness and that technological innovation and human capital jointly strengthen industrial performance. Fan and Jackson (2025), examining G20 countries over the period 1990–2022, showed that GDP per capita strongly supports technological innovation, while the effects of human capital and civil liberties remain more limited. Liu and Jackson (2026), using G20 data for the period 1990–2023, found that human capital strongly supports technological innovation, economic complexity increases innovation, and natural resource rents do not have a statistically significant effect.

Overall, the literature suggests that human development, human capital, innovation, ICT, economic complexity, green patents, digitalization, and technological indicators are closely related. However, three main gaps remain. First, many studies rely on panel data based on broad country groups, whereas Türkiye-specific time-series evidence remains limited. Second, several studies examine the effect of technology on human development rather than the effect of human development on technological progress. Third, technological progress is often measured through indirect indicators such as ICT investments, economic complexity, green patents, digitalization, or composite innovation indices. The present study addresses these gaps by focusing specifically on Türkiye over the period 1990–2023, using patent counts as a direct output-based proxy for technological progress, and applying time-series techniques that allow for structural breaks. In this respect, the study provides new evidence on whether human development contributes to technological progress in Türkiye under changing macroeconomic conditions.

2.3. Research Question and Hypotheses

Based on the theoretical framework and the empirical literature, the main research question of this study is whether human development has a statistically significant effect on technological progress in Türkiye. To address this question, the following hypotheses are proposed:

H_0: Human development has no significant effect on technological progress in Türkiye.
H_1: Human development has a significant effect on technological progress in Türkiye.

The formulation of these hypotheses is grounded in the theoretical linkage between human capital accumulation and innovation capacity. Improvements in human development—capturing dimensions such as education, health, and income—are expected to enhance individuals' productivity, facilitate knowledge diffusion, and strengthen a country's ability to generate and adopt new technologies. From an endogenous growth perspective, higher levels of human development contribute to technological advancement by fostering a more skilled and innovative workforce. Therefore, a statistically significant relationship between human development and technological progress is theoretically anticipated, although the direction and magnitude of this effect remain an empirical question to be tested within the context of Türkiye.

3. Data and Empirical Model

This study empirically analyses the relationship between human development and technological progress in Türkiye based on the model outlined in Equation (1).

$$\mathrm{lnPAT_t} = \alpha + \beta_1 \mathrm{lnHDI_t} + \beta_2 \mathrm{lnTRA_t} + \beta_3 \mathrm{lnEPU_t} + \varepsilon_t \quad (1)$$

The dependent variable, PAT, represents the level of patent-based technological output and is measured by the total number of patent applications (both resident and non-resident). The main independent variable, HDI, denotes the level of human development and is incorporated into the model using the human development index. TRA represents the process of economic globalization and is proxied by trade openness. Finally, EPU captures economic uncertainty and is included in the model using the world uncertainty index (WUI) for Türkiye as a proxy variable. Detailed information on the variables is provided in Table 1.

Table 1. Variable Definitions

Symbol	Description	Measurement	Source
PAT	Technological Progress	Patent applications	WDI
HDI	Human development	Human development index	UNDP
TRA	Economic Globalization	Trade openness (% of GDP)	WDI
EPU	Economic Uncertainty	World uncertainty index	FRED

Note: FRED: Federal Reserve Economic Data, WDI: World Development Indicator, UNDP: United Nations Development Programme.

The dataset covers annual observations for Türkiye over the period 1990–2023. The selection of the sample period is primarily driven by the availability of the human development index data, which begins in 1990. All variables are transformed into their natural logarithmic forms prior to the empirical analysis.

4. Econometric Methodology

The empirical strategy is designed considering both the characteristics of the data and the objectives of the study. Since the sample consists of annual observations covering the period 1990–2023, the analysis is based on a relatively limited number of observations. Furthermore, the Turkish economy experienced several economic crises, policy changes, and structural transformations during the sample period. Therefore, econometric methods capable of accounting for structural breaks and providing reliable long-run estimates under such conditions are preferred.

4.1. Unit Root Test

Conventional unit root tests do not account for structural breaks in time series. Perron (1989) emphasizes that failing to consider structural breaks when conducting unit root tests may lead to misleading inferences and estimations in the specified regression model. In this context, Perron (1989) proposes a unit root testing procedure in which the structural break is determined exogenously. However, the assumption of a known break date introduces a pretesting problem regarding the identification of the break point (Maddala & Kim, 1998). Zivot and Andrews (1992) criticize Perron's (1989) approach and develop an alternative test in which the structural break is determined endogenously. The Zivot–Andrews unit root test is based on three alternative model specifications:

$$y_t = \mu + \theta_1 DU(\lambda) + \beta t + \delta y_{t-1} + \sum_{j=1}^{k} \delta_j \Delta y_{t-j} + e_t \ \ (Model\ A) \tag{2}$$

$$y_t = \mu + \theta_2 DT(\lambda) + \beta t + \delta y_{t-1} + \sum_{j=1}^{k} \delta_j \Delta y_{t-j} + e_t \ \ (Model\ B) \tag{3}$$

$$y_t = \mu + \theta_1 DU(\lambda) + \theta_2 DT(\lambda) + \beta t + \delta y_{t-1} + \sum_{j=1}^{k} \delta_j \Delta y_{t-j} + e_t \ \ (Model\ C) \tag{4}$$

Model (A) captures structural changes in the intercept, Model (B) captures structural changes in the slope, and Model (C) allows for structural changes in both the slope and the intercept. In this framework, TB denotes the break date, while $\lambda = TB/T\ (\lambda \in (0.15, 0.85))$ represents the relative timing of the break. Furthermore, DU is defined as a dummy variable included in the models to capture a shift in the mean, whereas DT is a dummy variable that captures a structural change in the trend, and they are specified as follows:

$$DU_t = \begin{cases} 1 & t > TB \quad while \\ 0 & in\ other\ situation \end{cases}$$

$$DT_t = \begin{cases} t - TB & t > T\lambda \quad while \\ 0 & in\ other\ situation \end{cases}$$

The break date is identified as the point corresponding to the minimum t-statistic of the δ coefficient obtained from the model. Subsequently, this t-statistic is compared with the critical values reported in the Zivot–Andrews (ZA) table. If the absolute value of the calculated t-statistic exceeds the corresponding critical value, the null hypothesis is rejected.

4.2. Cointegration Test

Traditional cointegration tests tend to yield biased results, as they do not account for structural breaks in the estimation process. Moreover, researchers often lack prior information regarding the number of such breaks. To address this limitation, Maki (2012) cointegration test is employed, as it allows for an unknown number of structural breaks. The Maki (2012) procedure accommodates up to five structural breaks, which are determined endogenously. This approach builds upon the structural break methodology developed by Bai and Perron (1998), as well as the unit root testing framework proposed by Kapetanios (2005). Within this context, Maki (2012) introduces four alternative models to test the null hypothesis of no cointegration in the presence of structural breaks:

$$\text{Model 0: } y_t = \mu + \textstyle\sum_{i-1}^{k} \mu_i D_{i,t} + \beta' x_t + v_t \tag{5}$$

$$\text{Model 1: } y_t = \mu + \sum_{i-1}^{k} \mu_i D_{i,t} + \beta' x_t + \sum_{i-1}^{k} \beta' x_t D_{i,t} + v_t \tag{6}$$

$$\text{Model 2: } y_t = \mu + \sum_{i-1}^{k} \mu_i D_{i,t} + \gamma t + \beta' x_t + \sum_{i-1}^{k} \beta' x_t D_{i,t} + v_t \tag{7}$$

$$\text{Model 3: } y_t = \mu + \sum_{i-1}^{k} \mu_i D_{i,t} + \gamma t + \sum_{i-1}^{k} \gamma_i t D_{i,t} + \beta' x_t + \sum_{i-1}^{k} \beta' x_t D_{i,t} + v_t \tag{8}$$

where $t = 1, 2, \cdots, T$, k represents the maximum number of breaks, and $D_{i,t}$ is a dummy variable, in which $D_{i,t} = 1$ if $t > T_B$, and 0 otherwise. T_B presents the time period of the break. Models 0 and 1 are level shift and regime shift models, respectively. Adding a trend to Model 1 yields Model 2. Model 3 includes structural breaks in levels, trends, and regressors.

5. Empirical Results

The empirical analysis begins with an examination of the stationarity properties of the variables in order to avoid spurious regression results and to determine the appropriate econometric methodology. In time series analysis, identifying the order of integration is a crucial preliminary step, as it directly influences the selection of subsequent techniques, particularly those related to long-run relationships. In this context, the presence of unit roots in the series is tested by employing the Zivot–Andrews unit root test, which endogenously determines a single structural break in the series. This approach is particularly suitable for the Turkish economy, where structural changes arising from economic crises, policy shifts, and external shocks may lead to biased results if ignored. Therefore, incorporating structural breaks provides more reliable and robust evidence regarding the stochastic properties of the variables.

Table 2 reports the results of the Zivot–Andrews unit root test for technological progress, human development, trade openness, and economic policy uncertainty. The findings indicate that the null hypothesis of a unit root cannot be rejected at the level form for all variables, suggesting that the series are non-stationary in levels. However, when the first differences of the series are considered, the null hypothesis is rejected, implying that all variables become stationary after first differencing. In other words, the variables are integrated of order one, I(1). These findings have important implications for the subsequent stages of the analysis. Since the variables share the same order of integration, it becomes appropriate to investigate the existence of a long-run equilibrium relationship among them. Accordingly, the analysis proceeds with the Maki (2012) cointegration test, which allows for multiple structural breaks in the cointegration relationship. This method is particularly advantageous in capturing potential regime shifts and structural changes that may characterize the long-run dynamics of the Turkish economy.

Table 2. Zivot-Andrews Unit-Root Test

	Level		**First difference**	
	Test statistics	**Break date**	**Test statistics**	**Break date**
PAT	-4.329	2000	-6.940*	2005
HDI	-4.304	2009	-6.089*	2013
TRA	-4.655	2007	-7.589*	2015
EPU	-4.222	2012	-6.933*	2015

Note: *, ** and *** demonstrate statistical significance at the 1%, 5% and 10% level, respectively.

Table 3 presents the results of the Maki (2012) cointegration test, which allows for the possibility of multiple structural breaks in the long-run equilibrium relationship among the variables. This feature is particularly important in the context of the Turkish economy, where economic crises, policy reforms, and external shocks may induce regime shifts over time. The results indicate that the null hypothesis of no cointegration is rejected in Model 0, Model 1, and Model 2. This finding provides strong evidence that a stable long-run equilibrium relationship exists among technological progress, human development, and the other explanatory variables, even in the presence of structural breaks. In other words, although the variables may deviate in the short run, they tend to move together over the long run, converging toward a common equilibrium path.

Table 3. Maki Cointegration Test

	Test-statistics	**Critical values**			**Break dates**
		1 %	**5 %**	**10 %**	
Model 0	-5.344**	-5.820	-5.341	-5.101	1998
Model 1	-5.406***	-6.144	-5.645	-5.398	1996
Model 2	-8.079*	-7.767	-7.155	-6.868	1995 2005 2015
Model 3	-6.453	-7.737	-7.201	-6.926	2005 2015

Note: *, ** and *** demonstrate statistical significance at the 1%, 5% and 10% level, respectively.

Given the existence of cointegration, the next step involves the estimation of long-run coefficients. For this purpose, FMOLS (Phillips and Hansen, 1990) estimator is employed. FMOLS is particularly appropriate in cointegrated systems as it corrects for both endogeneity and serial correlation problems that typically arise in long-run regressions. By doing so, it provides unbiased and asymptotically efficient parameter estimates. Moreover, FMOLS helps to reduce small-sample distortions, thereby improving the reliability and robustness of the empirical results in finite samples, which is especially relevant in applied macroeconomic studies. To assess the robustness of the results, the estimated coefficients are further validated using DOLS (Stock & Watson, 1993) and CCR (Park, 1992) estimators.

Table 4 presents the estimated long-run coefficients. The FMOLS results indicate that human development has a positive and statistically significant effect on technological progress in Türkiye. This finding directly supports the main hypothesis of the study, namely that human development promotes technological progress. It also suggests that improvements in human development—reflected in better education, health, and income levels—contribute to the enhancement of technological capacity in the long run. Specifically, a 1% increase in human development leads to an approximately 5.744% increase in technological progress, highlighting a strong elasticity between the two variables. These results are consistent with Ranis (2011) and Lechman (2009), both of whom emphasize the positive relationship between human development and technological advancement. The results further show that trade openness exerts a positive and statistically significant impact on technology. Specifically, a 1% increase in trade openness increases technology by 0.528% in the long run. These findings are also consistent with Ranis (2011), who highlights the role of trade openness in reinforcing technological change. In contrast, economic policy uncertainty is found to have a negative and statistically significant effect on technological progress. The estimated coefficient implies that a 1% increase in economic policy uncertainty reduces technological progress by 0.113% in the long run. This result suggests that uncertainty in economic policies may discourage investment in innovation, weaken planning incentives, and slow down technological advancement.

Table 4. Long-Run Coefficient

	FMOLS		DOLS		CCR		VIF
Variable	**Coefficient**	**t-stat.**	**Coefficient**	**t-stat.**	**Coefficient**	**t-stat.**	
HDI	5.744*	9.081	6.034**	2.734	6.515*	10.035	7.572
TRA	0.528***	1.709	0.108	0.090	0.289	0.840	6.574
EPU	-0.113***	-1.902	0.438	1.478	-0.260*	-3.226	1.412
C	7.791*	5.827	10.388***	2.077	8.780*	6.079	-
D1998	-0.235**	-2.476	-0.511***	-1.964	-0.246**	-2.517	-
Adjusted R^2	0.706		0.726		0.680		

Note: *, ** and *** demonstrate statistical significance at the 1%, 5% and 10% level, respectively.

The DOLS and CCR results largely support the FMOLS findings for human development, although some differences emerge for trade openness and economic policy uncertainty. The positive effect of human development remains statistically significant across all estimators, with coefficient estimates ranging from 5.744 to 6.515. In contrast, the coefficients of trade openness become statistically insignificant under both DOLS and CCR estimations. Similarly, the negative effect of economic policy uncertainty remains significant only in the CCR specification, where a 1% increase in uncertainty reduces patent-based technological output by approximately 0.260%. These differences suggest that the estimated effects of trade openness and economic policy uncertainty are sensitive to the estimation technique employed. Therefore, the evidence regarding these two variables should be interpreted with caution, as the FMOLS findings are not fully corroborated by the alternative estimators. In contrast, the positive effect of human development remains robust across all three estimation methods, reinforcing the reliability of this finding. Furthermore, the VIF statistics given in Table 4 remain below the threshold value of 10, suggesting that multicollinearity is not severe. Overall, the results underline the importance of human development in fostering technological progress in Türkiye, while the effects of trade openness and economic policy uncertainty should be interpreted more cautiously due to their sensitivity to alternative estimation methods.

6. Discussion

The empirical findings indicate that human development has a positive and statistically significant effect on technological progress in Türkiye. This result supports the main hypothesis of the study and suggests that improvements in education, health, and overall living standards contribute to the country's capacity to generate technological outputs. In the Turkish case, the positive coefficient of the human development index implies that patent production should not be interpreted solely as the outcome of firm-level innovation efforts or conventional R&D incentives. Rather, it appears to be embedded in a broader development process in which social capabilities, human capital quality, and the overall level of welfare shape the environment for knowledge creation and innovation. In this sense, the results reinforce the idea that technological progress is closely linked to the depth and quality of human development. A stronger human development performance may improve the long-run innovation environment by increasing the stock of skilled and healthier individuals, supporting learning capacity, and strengthening the social basis of technological adaptation and invention. For Türkiye, this finding is particularly important because it suggests that policies aimed at increasing patent performance should be considered together with broader improvements in education, health, and social development, rather than being confined to narrow technology-oriented policy instruments alone.

The remaining variables in the model also provide important insights into the determinants of technological progress in Türkiye. The positive effect of trade openness indicates that integration with international markets may contribute to technological progress through knowledge diffusion, competition, and exposure to foreign technologies. By contrast, economic policy uncertainty has a negative and statistically significant effect, implying that unstable and unpredictable policy environments may discourage long-term innovation investments and weaken the incentives for technological upgrading. The structural breaks identified in the cointegration analysis—1997, 2002, and 2006—further indicate that the long-run relationship between human development and technological progress has evolved under different macroeconomic regimes. The break around 1997 may be interpreted in relation to increasing fragility in emerging markets and a less favorable external environment, while the 2002 break appears to reflect the restructuring period that followed the 2001 financial crisis in Türkiye. The 2006 break, in turn, may be associated with changes in global liquidity conditions and shifts in the external financial environment facing emerging economies. Taken together, these results suggest that technological progress in Türkiye has been shaped not only by human development, openness and uncertainty, but also by the broader macroeconomic stability of the economy and the changing conditions created by major periods of structural adjustment.

7. Conclusion

This study examined the long-run relationship between human development and technological progress in Türkiye over the period 1990–2023. Using patent counts as a proxy for technological progress and employing time-series methods that allow for multiple structural breaks, the analysis provided evidence of a stable long-run relationship among the variables. The results showed that human development has a positive and statistically significant effect on technological progress in Türkiye. Trade openness is also found to contribute positively to patent production, whereas economic policy uncertainty had a negative effect. These findings suggest that technological progress in Türkiye is shaped not only by economic performance and external openness, but also by broader human development conditions and macroeconomic stability.

From a policy perspective, the results imply that technology and innovation policies should not be limited to conventional R&D incentives alone. A more comprehensive policy framework is needed, one that strengthens education, health, and the broader foundations of human development while also maintaining a stable and predictable macroeconomic environment. In this respect, the findings indicate that improvements in human development can create a stronger basis for innovation and patent generation in the long run.

This study is subject to certain limitations. First, technological progress is represented only by patent counts, which may not capture all dimensions of innovation performance. Second, the analysis focuses only on Türkiye, limiting the possibility of cross-country comparison. Third, although the model incorporates several key macroeconomic determinants, some important drivers of technological development—such as R&D expenditures, the number of researchers, institutional quality, financial development, intellectual property rights, and high-technology exports—are not included due to data and scope constraints. Future research may extend the analysis by employing alternative indicators of technological progress, such as R&D output, innovation indices, or high-technology exports, incorporating additional determinants of innovation performance, and comparing Türkiye with other developing economies that share similar structural characteristics.

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