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RESEARCH ARTICLE

Technological Advancement, Income Inequality, and the Moderating Role of Education: Evidence from G-20 Countries

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Abstract

This study empirically investigates the relationship between technological advancement and income inequality, as well as the role of education within this relationship, using evidence from G-20 countries. The primary aim of the research is to test whether education functions as a moderation mechanism against the inequality-enhancing effects of technology. The analysis employs panel data covering the period 1996–2022 and is conducted using a Two-Way Fixed Effects (TWFE) model, which controls for unobserved heterogeneity across countries and years.

The findings indicate that technological advancement—measured by the logarithmic value of patent applications—has a significant and positive effect on income inequality (Gini coefficient), consistent with the Skill-Biased Technological Change (SBTC) hypothesis. However, the central contribution of the study lies in demonstrating the moderating role of education. The results show that in countries with higher levels of education, the inequality-enhancing impact of technological advancement is substantially weaker, highlighting the moderation function of education. In addition, empirical evidence supports a partial mediation mechanism operating through the technology → education → inequality channel. Overall, the results suggest that technology-driven inequality is not inevitable; rather, it can be mitigated through education investments and human capital policies. The findings underscore the need for G-20 countries to integrate technological advancement and education systems within a coherent policy framework in order to achieve more inclusive innovation outcomes.

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Introduction

Technological progress is one of the most decisive forces shaping the growth dynamics of contemporary economies and overall societal welfare. Over the past three decades, rapid advances in digitalization, automation, artificial intelligence, and high-technology production have significantly enhanced economic performance across countries; however, the implications of this transformation for income distribution have become increasingly contested. A growing body of research demonstrates that technological advancement reshapes wage structures by transforming skill demand in labor markets, with profound consequences for income inequality (Acemoglu & Restrepo, 2022; Xiao et al., 2024).

At the center of this debate lies the Skill-Biased Technological Change (SBTC) framework, which posits that technological progress is primarily complementary to skilled labor, raising wages in high-skill occupations while exerting a substitutive effect on routine and low-skill jobs (Acemoglu, 2002; Card & DiNardo, 2002). Task-based approaches further emphasize that technological transformation disproportionately disadvantages workers engaged in routine tasks, while increasing the earnings of those with analytical and technology-compatible skills (Acemoglu & Restrepo, 2022; Autor et al., 2006). These mechanisms suggest that, in the absence of equalizing policy interventions, technological progress may contribute to rising income inequality.

Within this context, education emerges as a central mechanism that both mitigates inequality and facilitates adaptation to technological change. Individuals with higher levels of education tend to acquire the skills required by technological transformation more rapidly, thereby enhancing both individual productivity and employment opportunities (Goldin & Katz, 2008). While there is strong empirical evidence that education can reduce income inequality by strengthening human capital (Gungor, 2010), the relationship between education and inequality is not uniformly equalizing. Rising returns to education, disparities in access to high-quality education, and structural inequalities in labor markets may constrain education's capacity to reduce inequality (Castelló-Climent & Doménech, 2014; Yang & Gao, 2018). Consequently, the role of education in the technology–inequality nexus must be examined along two distinct dimensions:

1. **Mediation**: Technological advancement may influence educational attainment, which in turn shapes income inequality.

2. **Moderation**: Education may either amplify or attenuate the effect of technological advancement on income inequality.

Empirical studies that systematically examine these two roles of education within a single analytical framework remain relatively scarce, and a notable gap persists in literature, particularly in the context of G-20 economies.

Given their substantial heterogeneity in both technological capacity and educational infrastructure, G-20 countries provide an especially suitable empirical setting for investigating how the technology–education–inequality nexus operates across different national contexts.

Addressing this gap, the present study employs panel data for G-20 countries covering the period 1996–2022 to empirically examine the impact of technological advancement on income inequality and to assess the dual role of education as both a mediating and a moderating mechanism in this relationship.

Accordingly, the study is guided by the following research questions:

1. Does technological advancement increase income inequality in G-20 countries?

2. Does education exhibit a mediating effect in the relationship between technological advancement and income inequality?

3. Does the level of education function as a moderating mechanism that attenuates the inequality-enhancing effect of technological advancement?

In this context, the study offers an original contribution to the literature by jointly examining the relationship between technology, education, and income inequality, and provides policy-relevant evidence on how education shapes and modifies technology-driven inequality.

1. Theoretical Framework

The relationship between technological advancement, income distribution, and education has become a rapidly expanding field of research over the past three decades. In particular, the rise of digitalization, automation, and the knowledge-based economy has profoundly transformed economic structures. The debate on the inequality effects of technological change is largely grounded in the Skill-Biased Technological Change (SBTC) framework.

According to the SBTC literature, technological progress increases the demand for high-skilled labor while reducing demand for low-skilled labor, thereby widening wage differentials (Autor et al., 2006; Tinbergen, 1974; Violante, 2018). Acemoglu (2002) emphasizes that technological progress alters the skill composition of production processes,

making long-run income inequality highly sensitive to the nature of technological change. Card and DiNardo (2002), while acknowledging the explanatory power of the SBTC framework, argue that it is insufficient to fully account for inequality trends across countries and highlight the critical role of institutional arrangements in shaping distributional outcomes.

A more recent interpretation of technological change is offered by the task-based automation approach, which analyzes the labor market effects of technology at the level of tasks rather than occupations. According to this perspective, automation transforms labor primarily by substituting machines for routine and repetitive tasks (Acemoglu & Restrepo, 2019). Acemoglu and Restrepo (2022) further demonstrate that while automation generates new tasks and restores demand for certain types of labor, it simultaneously leads to the permanent displacement of others.

Autor et al. (2020), focusing on the U.S. labor market, show that middle-income routine occupations have contracted rapidly, while employment has expanded at both the high-skilled and low-skilled ends of the distribution, thereby confirming the polarization of labor markets. Taken together, these findings indicate that technological change simultaneously affects processes of labor substitution and labor complementarity, and that the evolution of income inequality depends on the balance between these two mechanisms.

The relationship between technological innovation and income inequality is also closely linked to countries' levels of digitalization and innovation capacity. Xiao et al. (2024) demonstrate that technological innovation may deepen the digital divide and widen income disparities, particularly by reinforcing inequality through limited access to technology among low-income groups. Similarly, Fiedler et al. (2021) find that automation and digitalization have intensified income inequality across European countries. In parallel, Milanovic (2016) argues that global inequality has acquired a structural character, with technological transformation acting as a key force accelerating this process. The OECD (2015) further emphasizes that high levels of inequality generate adverse effects on economic growth and underscores the necessity of policy interventions to ensure that the gains from technological progress are more broadly shared across society.

Education plays a central role in shaping both technological transformation and income inequality. Goldin and Katz (2008) argue that the "race" between technological change and education is a key determinant of the direction of inequality, suggesting that wage disparities widen when the supply of education lags behind technological demand. Similarly, Lemieux (2006) demonstrates that the expansion of higher education has pronounced effects on wage inequality. Kim and John (1999) contend that technological change stimulates investments in human capital and that a strong complementarity exists between education and economic growth. Focusing on the Turkish context, Gungor (2010) finds that education contributes to economic growth by enhancing labor quality and improving the distribution of human capital. Yang and Gao (2018) further show that the impact of educational expansion on wage inequality varies depending on the nature and effectiveness of countries' education policies.

Another key mechanism reshaping the relationship between technology and inequality is the mitigating role of education in offsetting the adverse effects of automation. Bentaouet Kattan et al. (2021) demonstrate that education significantly reduces the negative impact of automation on wage inequality and that economies with higher educational attainment are more resilient to technological transformation. This finding suggests that the effect of technology on inequality is conditioned by countries' human capital structures. Lucas (1988) and Barro (1991) further establish education as a fundamental driver of economic growth, showing that differences in human capital help explain cross-country disparities in development levels. Mincer (1989) emphasizes that human capital responses are decisive in shaping labor market outcomes in the face of technological change.

The broader literature on the social welfare implications of technological change demonstrates that, when technological gains are not distributed equitably across society, economic and social vulnerabilities tend to intensify. Acemoglu and Johnson (2023) argue that technological progress does not inherently generate widespread prosperity; rather, in the absence of guiding political institutions and robust educational systems, it may exacerbate existing inequalities.

Piketty (2014) similarly shows that income and wealth disparities have become structural features of modern capitalism, with technological advances accelerating capital returns relative to labor income. Stiglitz (2009) further contends that conventional measures of economic performance fail to capture rising inequality, noting that technological transformation does not automatically translate into social progress. In line with these perspectives, the Global Sustainable Development Report (2015) emphasizes that for technological developments to support inclusive

growth, they must be accompanied by strong institutions, effective social policies, and comprehensive investments in education.

In sum, the literature demonstrates that technological progress exerts strong yet conditional effects on income inequality, and that the direction and magnitude of these effects vary substantially across countries depending on their educational attainment, human capital composition, and institutional structures. While the SBTC and task-based automation frameworks show that technology reshapes skill demand in ways that can amplify inequality, the education literature highlights the capacity of human capital to mitigate these pressures. Consequently, education emerges as a central policy lever capable of cushioning the inequality-enhancing effects of technological change, thereby playing a pivotal role in ensuring that technological advancement becomes compatible with inclusive economic growth.

2. Methodology

This study examines the relationships among technological advancement, education, and income inequality by utilizing annual panel data for G-20 countries covering the period 1996–2022. The dataset is structured at the country–year level, and after removing missing observations and retaining overlapping periods across all variables, the final analytical sample consists of **146 country-year observations**. A panel data framework is particularly suitable for analyzing the technology–education–inequality nexus, as it enables the simultaneous assessment of both cross-country structural heterogeneity and temporal dynamics (Baltagi, 2005).

To address unobserved heterogeneity, the analysis employs a **Two-Way Fixed Effects (TWFE)** model, which controls for time-invariant country-specific characteristics as well as global shocks that affect all countries in a given year. By incorporating these country and year fixed effects, the model effectively mitigates the risk of omitted variable bias arising from latent factors such as cultural attributes, institutional traditions, or historically embedded country-level characteristics.

2.1 Data Set and Variables

The dependent variable of the study is **income inequality**, measured by the Gini coefficient.

The key independent variable, **technological advancement**, is operationalized using World Bank data on total patent applications (residents + nonresidents), expressed as the logarithm of patent applications per capita. The log transformation mitigates extreme right-skewness in the distribution and enhances the robustness of the model estimates.

The mediating and moderating variable, **education**, is represented by the logarithmic transformation of the net secondary school enrollment rate. This variable is examined both as an outcome influenced by technological advancement (mediation analysis) and as a conditioning factor that alters the strength of the relationship between technology and inequality (moderation analysis).

Control variables included in the model are:

- Per capita GDP (log) - (lnGDP_pc)
- Total unemployment rate - (%)
- Trade openness (measured as the ratio of exports plus imports to GDP), which account for macroeconomic factors known to influence income distribution Dynamics.

These variables allow the model to isolate the relationship between technology and income inequality more precisely by accounting for macroeconomic factors known to influence inequality. All variables were obtained from the World Bank's World Development Indicators (WDI) database. To construct a consistent panel structure, years with missing observations were removed and appropriate logarithmic transformations were applied. The final dataset contains a sufficient number of country-year observations for reliable estimation using the TWFE framework.

2.2. Econometric Approach

The core of the empirical analysis relies on the following TWFE model, designed to isolate the effect of technological advancement on income inequality:

$$Gini_{it} = \beta_0 + \beta_1 \ln(Patent_{it}) + \beta_4 Kontrol_{it} + \mu_i + \lambda_t + \epsilon_{it}.$$

In this specification, $\mu_i$captures time-invariant country-specific characteristics, while $\lambda_t$represents global economic and political shocks that affect all countries simultaneously. This structure enables the model to estimate the relationship between technology and inequality net of persistent unobserved heterogeneity. Robust standard errors are employed to address potential heteroskedasticity and autocorrelation, thereby enhancing the reliability of statistical inference regarding the estimated coefficients.

2.3. Mediation Analysis

To examine whether education functions as a mediating mechanism in the relationship between technological advancement and income inequality, a two-step mediation strategy is employed:

Technology → Education:

$$Eğitim_{it} = \alpha_0 + \alpha_1 \ln(Patent_{it}) + \alpha_4 Kontrol_{it} + \mu_i + \lambda_t + u_{it}$$

Technology + Education → Inequality:

$$Gini_{it} = \beta_0 + \beta_1 \ln(Patent_{it}) + \beta_2 Eğitim_{it} + \beta_4 Kontrol_{it} + \mu_i + \lambda_t + \epsilon_{it}$$

The change in the coefficient of the technology variable once education is included in the model provides evidence of partial mediation. This framework illustrates how technological advancement may indirectly influence inequality by increasing the level of education.

2.4. Moderasyon Analysis

To assess whether education attenuates the effect of technological advancement on income inequality, an interaction term between education and technology is incorporated into the model:

$$Gini_{it} = \beta_0 + \beta_1 \ln(Patent_{it}) + \beta_2 Eğitim_{it} + \beta_3 (\ln(Patent_{it}) \times Eğitim_{it}) + \beta_4 Kontrol_{it} + \mu_i + \lambda_t + \epsilon_{it}.$$

In this specification, the coefficient $\beta_3$of the interaction term determines the direction of the moderation effect:

- A negative and statistically significant coefficient indicates that education weakens the inequality-enhancing effect of technological advancement.
- A positive coefficient, on the other hand, indicates that education amplifies this effect.

This approach enables both roles of education to be evaluated holistically within the same dataset.

2.5. Model Suitability

The TWFE approach is well suited for causal inference in heterogeneous country groups such as the G-20, where institutional and structural differences are substantial. In this study, a random effects (RE) model is not employed; the methodological strategy is built directly on the fixed effects framework, and all estimations are carried out using the TWFE specification. Consequently, neither the Hausman test nor the Hausman–Taylor estimator is required, as the model is explicitly designed around the fixed effects structure.

4. Findings

This section presents the results of the panel data models estimated to examine the relationships among technological advancement, education, and income inequality. The analyses are conducted using a Two-Way Fixed Effects (TWFE) framework on the G-20 panel dataset covering the period 1996–2022. Controlling for both country and

year fixed effects allows the estimations to net out unobserved institutional and structural heterogeneity, as well as global economic shocks, thereby yielding more reliable coefficient estimates.

4.1. Descriptive Statistics and Correlations

Preliminary analyses reveal the general patterns among inequality, patent intensity, education, and the control variables. The average Gini coefficient in G-20 countries is approximately 0.39, indicating a medium-to-high level of income inequality. The logarithmic value of patent applications per capita exhibits substantial cross-country variation: advanced economies such as the United States, Japan, and South Korea display high levels of technological activity, whereas countries like Turkey, Mexico, and South Africa show considerably lower values.

The correlation matrix indicates a positive association between technological advancement and income inequality, and a negative association between education and income inequality. These initial patterns are consistent with the predictions of the SBTC framework and the theoretical expectation that education mitigates inequality. However, the direction and magnitude of causality cannot be inferred without formally estimating the TWFE models

4.2. Panel Fixed Effects (FE) Models

The main findings of Model 1, which tests the direct effect of technological advancement on inequality; Model 2, which examines its effect on education; Model 3, which investigates the mediating role of education; and Model 4, which incorporates the education–technology interaction term, are summarized in Table 1 below.

Tablo 1. TWFE Sonuçları (Bağımlı Değişken: Gini ve Eğitim)

Değişken	Model 1 (Gini)	Model 2 (Eğitim)	Model 3 (Gini)	Model 4 (Gini – Moderasyon)
ln(Patent_pc)	**+0.083** (0.038)*	**+0.088** (0.041)*	**+0.079** (0.039)*	**+0.091** (0.044)*
Education	—	—	**–0.0018** (0.0007)*	**–0.0021** (0.0008)*
lnGDP_pc	–0.0078 (ns)	**+0.0051** (0.001)**	–0.0039 (ns)	–0.0055 (ns)
Unemployment	**+0.0051** (0.001)**	–0.0001 (ns)	**+0.0044** (0.001)**	**+0.0047** (0.001)**
Trade Openness	**–0.0182** (0.007)**	+0.0004 (ns)	**–0.1385** (0.024)**	**–0.1279** (0.026)**
Interaction (lnPatent × Education)	—	—	—	**–0.0049** (0.002)*
Country Fixed Effects	Var	Var	Var	Var
Year Fixed Effects	Var	Var	Var	Var
Number of Observations	146	146	146	146

Note: * p<0.05, ** p<0.01; ns = statistically insignificant.

4.3. The Direct Impact of Technology on Inequality (Model 1)

The coefficient of the ln(Patent_pc) variable is positive (+0.083) and statistically significant. This finding indicates that technological advancement increases income inequality in G-20 countries. The magnitude of the effect is

moderate due to the logarithmic transformation, implying that an increase in patent intensity widens the income distribution.

This result is consistent with the Skill-Biased Technological Change (SBTC) theory (Acemoglu, 2002) and the task-based automation literature (Autor et al., 2006). Thus, technology initially operates in favor of high-skilled labor, exerting an inequality-enhancing effect.

4.4. The Effect of Technology on Education (Model 2)

The findings of Model 2 reveal that technological advancement exerts a positive and statistically significant effect on the level of education ($\beta \approx +0.088$). This result aligns with theoretical expectations suggesting that technology increases the demand for human capital and stimulates educational investment across countries. The evidence implies that the education channel is active—technology promotes the expansion of education while simultaneously establishing the first stage of the mediation mechanism.

4.5. Mediation Role of Education (Model 3)

When education is included in the model:

- The coefficient of education is negative and statistically significant (–0.0018), indicating that education reduces inequality.

- The coefficient of technological advancement (lnPatent_pc) remains positive and significant, suggesting that the inequality-enhancing effect of technology does not completely disappear.

This pattern supports the presence of a partial mediation mechanism, characterized by the following dynamics:

1. Technology exerts a positive effect on education.

2. Education reduces inequality.

3. However, education cannot fully offset the inequality-enhancing impact of technology.

Therefore, technology simultaneously increases inequality directly while generating an indirect, inequality-reducing mechanism through education.

4.6. The Moderating Role of Education (Model 4)

The most critical mechanism examined in this study is the moderating role of education in the technology–inequality relationship. The coefficient of the interaction term is negative (–0.0049) and statistically significant ($p < 0.05$). This indicates that as the level of education increases, the inequality-enhancing effect of technological advancement weakens.

In other words, education functions as a moderation mechanism that mitigates the adverse distributional effects of technology. A higher level of education enhances societies' adaptive capacity to technological transformation and limits the pressure that technological shocks exert on income distribution.

4.7. Overall Assessment

When all models are evaluated together, the following framework emerges:

1. Technological advancement directly increases income inequality.

2. Technology simultaneously enhances the level of education.

3. Education exerts an inequality-reducing effect.

4. Education plays a moderation role, weakening the inequality-enhancing impact of technology.

This integrated structure is fully consistent with the theoretical framework proposed throughout the study. It demonstrates that countries with stronger and more adaptive education systems are better equipped to manage and mitigate the adverse distributional consequences of technological transformation.

CONCLUSION

This study examined the relationship between technological advancement and income inequality in the context of G-20 countries, assessing whether education plays both a mediating (mediation) and moderating (moderation) role within this relationship.

Using panel data covering the period 1996–2022 and employing the Two-Way Fixed Effects (TWFE) approach, the analyses reveal that technological advancement—measured by the logarithmic value of patent applications—has a statistically significant and positive effect on income inequality.

This finding is consistent with the theoretical literature suggesting that as technology advances, the demand for high-skilled labor increases, routine tasks are replaced through automation, and labor markets become increasingly polarized—all of which contribute to widening income disparities.

The analyses further reveal that technological advancement has a positive impact on educational attainment. This finding indicates that as innovative sectors expand, the demand for education rises, prompting education systems to adapt to the requirements of technological transformation. When the effect of education on inequality is examined, the results show that higher levels of education reduce income inequality. This pattern provides empirical evidence for a partial mediation mechanism, in which technology indirectly influences inequality through its positive effect on education.

The most salient finding of the study concerns the moderating role of education in the technology–inequality relationship. The interaction term is negative and statistically significant, indicating that the inequality-enhancing effect of technology weakens as the level of education increases. This suggests that education systems enhance individuals' capacity to adapt to technological change, thereby mitigating the adverse distributive consequences of technological progress. Consequently, societies with higher educational attainment are better equipped to manage the inequality pressures generated by technological advancement.

These findings offer important policy implications. First, it is evident that technological advancement and education policies must be pursued in a coordinated manner. Policies that focus solely on enhancing innovation capacity may inadvertently exacerbate inequality if the education system fails to accompany this transformation. In rapidly transforming economies such as those of the G-20 countries, increasing inclusive and high-quality investments in secondary and tertiary education is critical to mitigating the adverse effects of technology on income distribution. Furthermore, human capital policies should be redesigned to align with the evolving skill demands generated by technological progress, ensuring that the workforce can effectively adapt to new production paradigms and benefit from the opportunities of digital transformation.

In conclusion, the increase in inequality driven by technological progress is neither automatic nor inevitable. This study demonstrates that education determines both the direction and magnitude of the relationship between technological advancement and income inequality through its dual roles as a mediating and moderating mechanism. Therefore, to ensure that technological transformation produces more inclusive and balanced social outcomes, education policies must be placed at the core of development strategies. The findings underscore the importance of approaching technology and education within an integrated and long-term strategic framework, particularly for the G-20 economies but also for all nations seeking to align technological progress with equitable and sustainable growth.

Ethical Considerations

This study is based exclusively on secondary data obtained from publicly available international databases covering G-20 countries. No primary data collection involving human participants, personal data, or confidential information was conducted. Consequently, ethical approval from an institutional review board was not required. The research was carried out in accordance with established principles of academic integrity, transparency, and responsible data use. All data sources were properly acknowledged, and the analysis was conducted with due care to ensure accuracy, reproducibility, and objectivity.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper. The research was conducted independently, and no financial, professional, or personal relationships influenced the study design, data analysis, interpretation of results, or manuscript preparation.

Conference Submission Note

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