THE ROLE OF TECHNOLOGICAL DIVIDE BETWEEN RURAL AND URBAN AREAS ON FINANCIAL AND HUMAN CAPITAL [1]

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ABSTRACT | Technological innovations are reshaping today's world, and digitalization has become a key driver influencing national economies. This study investigates the determinants of total factor productivity (TFP) changes across 12 Turkish regions from 2011 to 2023 within the framework of Digital Divide Theory. Employing the Malmquist Index, it assesses the impact of technological disparities on financial and human capital. Results show that the West Marmara, Mediterranean, and Black Sea regions demonstrated high technical efficiency, while Istanbul and the Aegean regions led in technological progress and TFP growth. Deposit distribution, education levels, and R&D human resources positively affected productivity in developed regions. However, income inequality and R&D expenditure had weaker effects than expected, indicating that these factors alone cannot explain regional TFP gaps. The study highlights efficient R&D use, reduced input waste, and technological transformation as vital for sustainable regional development in Turkey.

Keywords: *Technological divide, financial capital, human capital, productivity*
JEL Code: *R11, O15, O16, O32, O47*

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[1] Compliance with the ethical rules of the relevant study has been declared.

KIRSAL VE KENTSEL BÖLGELER ARASINDA TEKNOLOJİK BÖLÜNMENİN FİNANSAL VE BEŞERÎ SERMAYE ÜZERİNDEKİ ROLÜ

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ÖZ | Teknolojik yeniliklerin şekillendirdiği günümüzde dijitalleşme, ülke ekonomilerini farklı dinamikler üzerinden etkileyen önemli bir unsur haline gelmiştir. Bu çalışma, Dijital Bölünme Teorisi çerçevesinde 2011-2023 döneminde Türkiye'nin 12 bölgesinde teknolojik bölünmenin finansal ve beşerî sermaye üzerindeki etkilerini, toplam faktör verimliliği (TFV) değişimleri üzerinden incelemektedir. Malmquist Endeksi kullanılarak yapılan analizde, Batı Marmara, Akdeniz, Batı ve Doğu Karadeniz bölgeleri teknik etkinlikte; İstanbul ve Ege bölgeleri ise teknolojik etkinlikte öne çıkmıştır. İstanbul, Ege ve Akdeniz bölgeleri TFV artışında en verimli bölgeler olarak belirlenmiştir. Bulgular, mevduat dağılımı, eğitim düzeyi ve Ar-Ge insan kaynağının verimlilik üzerinde olumlu etkiler yarattığını; ancak gelir eşitsizliği ve Ar-Ge harcamalarının etkisinin beklenenden düşük kaldığını göstermektedir. Sonuç olarak, Ar-Ge kaynaklarının etkin kullanımı, âtıl girdilerin azaltılması ve teknolojik dönüşümün teşviki sürdürülebilir kalkınma için temel stratejilerdir.

Anahtar Kelimeler: *Teknolojik bölünme, finansal sermaye, beşerî sermaye, verimlilik.*
JEL Kodları: *R11, O15, O16, O32, O47*

1. INTRODUCTION

The world is currently undergoing major transformations alongside globalization (Ersezer & Altun, 2024, p. 15). Historically, the most profound shifts in labor and social structures occurred during the Agricultural and Industrial Revolutions (Yankın, 2019, p. 3). Social scientists describe the Industrial Revolution as a turning point that irreversibly transformed preexisting systems. Similarly, today's digital transformation—often referred to as the Fourth Industrial Revolution—has comparable potential to reshape societal and economic structures (Republic of Turkey Ministry of Development, 2023, p. 33).

Digitalization has become a key driver of global economic development by enhancing efficiency, productivity, and competitiveness, while also generating new occupations (Kıyak, 2023, p. 141). Yet, it brings uncertainties, especially concerning employment (Ersezer & Altun, 2024, p. 15). Automation may reduce the demand for certain jobs, with effects varying by education level. Those with lower education may face greater risks, whereas individuals leveraging technology can gain productivity advantages. Hence, forecasting digital transformation's impacts and formulating policies for vulnerable groups are essential (Republic of Turkey Ministry of Development, 2023, p. 34).

In Turkey, digitalization has raised concerns about potential job losses and increased unemployment. A 2014 study showed that innovative jobs represented a small share of total employment, indicating that while digital effects may seem limited, high service-sector employment heightens automation risks. Research further suggests that 58% of men and 61% of women face a high risk of job displacement (Özen, 2017, pp. 2-4).

The COVID-19 pandemic accelerated remote work, emphasizing the importance of reliable internet and digital infrastructure. However, unequal access persists, particularly between regions, creating a growing "digital divide" (OECD, 2020). In Turkey, open and distance education initiatives have expanded rapidly, reshaping traditional educational models (Sezgin & Fırat, 2020, p. 38). Yet, digitalization may transform social inequalities into technological disparities between urban and rural populations (Kostyaev, 2024, p. 50).

The "digital divide" reflects inequalities in access to information and communication technologies (ICTs) and internet use across socio-economic groups (OECD, 2001). It encompasses disparities in connectivity, digital equipment, and ease of use (Stevenson, 2009, p. 2; Sparks, 2013, p. 29; Van Dijk, 2017, p. 200; Helsper, 2021, p. 108). According to the European Commission (2012), ICTs have become integral to social, educational, and professional life, making equal access essential for social equity and governance.

Thus, digital transformation-much like the Industrial Revolution-has brought irreversible changes to education, labor markets, and access to resources. Assessing its effects on Turkey's economy is therefore vital. Developing a comprehensive national strategy will be key to sustaining international competitiveness (Republic of Turkey Ministry of Development, 2023, p. 33).

This study aims to identify the characteristics and quantitative parameters of digital inequality between urban and rural populations in Turkey and propose policy solutions (Kostyaev, 2024, p. 50). It contributes to two areas of literature: first, by analyzing how the technological divide affects financial and human capital in relation to total factor productivity, using MI analysis for regional comparisons (Yartey, 2008; Švarc et al., 2021; Xiao et al., 2024). Second, it provides region-specific insights on which variables require improvement, extending findings from prior studies (Wijers, 2010; Carlson & Isaacs, 2018; Peng & Dan, 2023). This research builds upon and complements the results of Quibria et al. (2003), Chang et al. (2012), and Mahapatro (2021), using eight ICT indicators over 2011-2023-a comparatively longer analysis period.

The conceptual framework and originality of this study are presented in the introduction, followed by sections on literature, methodology, findings, and policy recommendations for Turkey's regions.

Turkey's economy is composed of 12 statistical regions, each exhibiting distinct economic and developmental characteristics. While Istanbul, the Aegean, and the Western Anatolia regions dominate in industrial production, financial capital, and R&D investments, the Eastern and Southeastern Anatolia regions rely more heavily on agriculture and have lower human capital accumulation. The Marmara and Mediterranean regions stand out with dynamic service and tourism sectors, whereas the Black Sea regions maintain more balanced structures with moderate industrial and agricultural outputs. These disparities reflect persistent regional development gaps, which directly influence the distribution and efficiency of both financial and human capital. Understanding how such differences shape total factor productivity (TFP) under digital transformation is therefore critical to this study's regional analysis framework.

Accordingly, this study seeks to answer the following central research question: How does the technological divide influence total factor productivity (TFP) across Turkey's regions through financial and human capital dynamics?

In line with this question, the study tests the following hypotheses:

H1: *Regional differences in financial and human capital significantly explain variations in total factor productivity (TFP) within the framework of the Digital Divide Theory.*

H2: *Regions with higher levels of digitalization and R&D-based human capital accumulation exhibit stronger TFP growth.*

H3: *The effect of the technological divide on productivity varies across development levels, indicating that the impact of digitalization on regional efficiency is not uniform.*

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

The foundation of this study is grounded in neoclassical growth theory, particularly the Solow–Swan model, which emphasizes capital accumulation, labor input, and technological progress as the principal determinants of economic growth and productivity. According to Solow's framework, long-term growth cannot be sustained solely through increases in capital and labor; it depends on technological advancement that enhances total factor productivity (TFP). In this context, TFP represents the efficiency with which financial and human capital are utilized to generate output.

Recent developments in the digital economy extend this framework by considering digitalization as a new form of technological progress. Digital technologies improve capital efficiency, labor productivity, and innovation capacity, but their diffusion is often uneven across regions, creating what is termed a digital divide. The Digital Divide Theory explains disparities in digital access, skills, and outcomes, suggesting that regions with higher digital penetration and human capital tend to achieve greater productivity gains.

In Turkey, economic structures vary significantly across 12 regions, which differ in terms of industrial concentration, digital infrastructure, and educational attainment. Developed regions such as Istanbul, the Aegean, and Western Anatolia exhibit higher R&D intensity and financial accumulation, whereas Eastern and Southeastern Anatolia remain dominated by agriculture and lower human capital accumulation. These differences lead to varying capacities to absorb and benefit from digital transformation, thereby influencing regional productivity dynamics. This study thus integrates Solow's growth model with the Digital Divide framework to analyze how technological disparities across regions shape TFP dynamics.

Within this scope, we can summarise the literature surrounding the theoretical framework of the study as follows:

Assadi (2024) conceptualizes digital poverty as a new form of inequality arising from technological advancement, analyzing internet access rates both globally and within Turkey. Similarly, Kostyaev (2024) examines inequalities in digital access, competence, and technology use across Russian regions, finding that while access disparities have narrowed, gaps in digital competence have widened.

In the Turkish context, Ay and Kılıç (2023) identify four geographical dimensions of digital inequality, concluding that regional imbalances in infrastructure, income, and culture deepen the urban-rural divide. Kıyak (2023) focuses on digitalization strategies of manufacturing firms in the TR32 region, revealing that 68% have low digital maturity, which underscores the uneven technological adaptation among industries.

At the macro level, Peng and Dan (2023) analyze China's urban-rural income inequality and discover a U-shaped relationship between the digital economy and income disparities, confirming the presence of regional threshold effects-a concept also relevant to Turkey's uneven development pattern. Similarly, Güngör Karyağdı (2022) explores the banking sector in the TRB2 region and highlights both efficiency gains and employment risks of digital transformation, reflecting the dual nature of technological change identified in the Solow framework.

The relationship between digitalization and economic growth has also been empirically supported. Bulut and Çizgici Akyüz (2020) find that digital banking positively affects economic growth in both the short and long term, while Nerse (2020) reveals that the COVID-19 pandemic intensified digital inequalities in education, particularly between rural and urban populations. Çark (2020) emphasizes that Industry 4.0 technologies are reshaping the labor market, potentially eliminating or transforming certain professions, thereby affecting the labor component (L) of productivity growth.

From a broader intellectual capital perspective, Švarc et al. (2021) note that limited theoretical and empirical work links intellectual capital to digital transformation, particularly within the EU, and propose a conceptual model integrating digitalization and human capital dimensions-an approach that aligns with the K-L-TFP relationship in this study. Similarly, Gladkova and Ragnedda (2020) assess the three-level digital divide (access, skills, benefits) across Russian regions, finding that socio-economic and infrastructural disparities strongly determine digital performance.

On a micro-level, Hui et al. (2013) analyze a community computing project in rural China and develop a "digital inequality pyramid" to classify individuals by access and literacy levels. Their findings indicate that digital literacy programs can help individuals move upward in this pyramid, reducing inequality-an implication that parallels Turkey's need for policies enhancing regional human capital.

Overall, the reviewed literature demonstrates that digital inequality is a multi-dimensional issue shaped by access, skills, and socio-economic conditions. Studies consistently show that digital transformation affects productivity through both financial and human capital channels. However, few studies integrate these dimensions into a comprehensive framework connecting digitalization with total factor productivity at the regional level.

The reviewed studies collectively highlight the significance of digitalization and the persistence of digital inequality, yet most remain limited in scope or theoretical integration. Assadi (2024) and Kostyaev (2024) identify the multi-dimensional nature of digital inequality but do not link it to productivity outcomes. Our study addresses this gap by examining how digital disparities translate into total factor productivity (TFP) differences across regions through financial and human capital channels. While Ay and Kılıç (2023) map regional digital inequalities and Kıyak (2023) and Güngör Karyağdı (2022) provide sectoral insights, these works lack a macro-regional productivity perspective. We extend their findings by applying the Malmquist Index to measure regional efficiency and technological progress within a unified analytical framework. Similarly, studies such as Peng and Dan (2023), Bulut and Çizgici Akyüz (2020), and Çark (2020) explore the economic effects of digitalization but overlook spatial disparities. Our analysis explicitly incorporates regional heterogeneity, revealing how unequal digital readiness and capital distribution shape productivity dynamics. Finally, Švarc et al. (2021), Gladkova and Ragnedda (2020), and Hui et al. (2013) underscore the role of intellectual and human capital in digital transformation but focus on non-Turkish contexts. We contribute by situating these theoretical insights within Turkey's regional framework, linking the Digital Divide Theory with the Solow model to analyze how K and L factors mediate TFP growth.

By adopting the Solow model as its theoretical foundation and incorporating digitalization as a modern productivity driver, the study provides a coherent framework to interpret regional efficiency and technological progress in the context of the digital economy. In summary, previous studies have largely examined digital inequality descriptively or sectorally. This study advances the literature by integrating digital divide dynamics into a productivity-based regional model, providing a comprehensive empirical framework to explain how digital transformation drives regional efficiency in Turkey.

3. METHODOLOGY AND DATA

In this study, Total Factor Productivity (TFP) was not derived through a parametric residual calculation as in the traditional Solow model, but rather estimated using a non-parametric Data Envelopment Analysis (DEA) framework based on the Malmquist Index (MI) approach. Unlike the Solow residual method, which relies on predetermined factor shares for capital (K) and labor (L) and assumes a specific production function, the MI approach measures the relative efficiency change over time by comparing multiple observed inputs and outputs across decision-making units (DMUs).

This methodological choice allows us to capture productivity dynamics without imposing functional form restrictions and to account for multiple dimensions of input use beyond single K and L factors. Accordingly, variables such as R&D expenditures are used as proxies for capital accumulation and education-related indicators are used to represent human capital quality. These proxies reflect the broader composition of inputs driving technological and efficiency change at the regional level.

Given this framework, capital depreciation (amortization) calculations inherent in the Solow model are not directly applicable to our analysis. The MI-based DEA approach evaluates productivity change through shifts in the efficiency frontier rather than through adjustments in factor depreciation or marginal productivity parameters. This distinction ensures that the measurement of TFP in this study reflects relative performance and technological progress among Turkey's 12 regions, consistent with the objectives of regional comparative analysis.

The Malmquist Productivity Index (MPI), originally defined as a quantity index by Malmquist (1953), measures the change in total factor productivity (TFP) between two observations as the ratio of distances from a common technology. Building upon this foundation, Sten Malmquist introduced the idea of constructing an index through the "distance function." Since this index was initially developed within a consumption framework, where utility is measured only ordinally, the concept of economies of scale was not considered at that time.

However, the Malmquist quantity index gained analytical significance through the pioneering works of Caves et al. (1982), as well as Nishimizu and Page (1982). While the former focused on the theoretical foundations of the index, the latter emphasized its utility in applied analyses. These studies demonstrated that the Malmquist index not only evaluates productivity in production processes but also captures the effects of technological progress. Moreover, its potential use in comparative productivity analyses across countries and sectors was highlighted.

This application became even more prominent with the development of non-parametric linear programming techniques by Färe et al. (1995), which enabled the practical calculation of the MPI. Consequently, the MPI evolved from a theoretical construct into a widely applied measurement tool. In contrast to the consumer context in which it was originally developed, economies of scale play a critical role in the producer context, where efficiency boundaries are determined by technological and environmental constraints.

The MPI has thus become a dynamic and versatile method for measuring and tracking changes in resource efficiency and total factor productivity (TFP) over time. It is frequently used to compare the productivity of a production unit, such as a firm, across two different time periods. As emphasized by Oh (2010), the flexibility of the Malmquist index enhances its adaptability to various production conditions and datasets. Furthermore, its capacity to jointly account for environmental and economic factors provides a comprehensive perspective on resource use efficiency and sustainability.

In this context, generalizations of the traditional formulation have further increased the flexibility of the MPI for both input- and output-oriented analyses (Grifell-Tatjé & Lovell, 1999). The index is calculated as the product of two fundamental components: “catch-up” and “frontier shift.” The catch-up component measures a firm’s efficiency improvement relative to the best practice frontier, while the frontier shift component reflects changes in the frontier itself between two periods (Pires & Fernandes, 2012; Telli & Serin, 2022).

The MPI thus introduces a time dimension to efficiency analysis, enabling the evaluation of productivity changes over time. However, unlike its original consumer-based formulation, economies of scale become crucial in the producer framework. Specifically, shifting efficiency frontiers in production highlight the importance of incorporating both technological advances and environmental constraints. Therefore, the MPI decomposes productivity changes into two main components: Technical Efficiency Change (TEC) and Technological Change (TC) (Färe et al., 1994).

Moreover, TEC can be further divided into Pure Efficiency Change (PEC) and Scale Efficiency Change (SEC). Accordingly, total factor productivity change (TFPC) is computed as the product of TEC and TC, while TEC itself equals the product of PEC and SEC. This decomposition allows researchers to identify whether productivity changes are driven by improvements in efficiency or by shifts in technology. A TFPC value greater than 1 indicates an increase in productivity, a value below 1 indicates a decrease, and a value equal to 1 denotes no change (Cooper et al., 2007; Kim et al., 2012). These relationships are typically illustrated in diagrams, as shown by Li and Liu (2010).

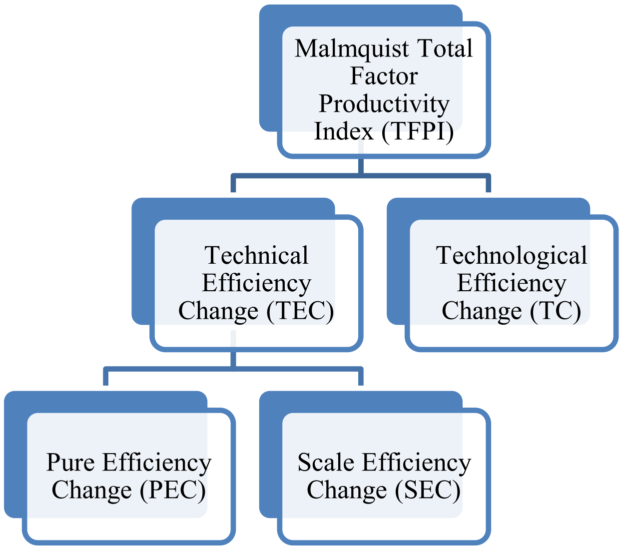

Figure 1: Malmquist Total Factor Productivity Analysis

The calculations for the Total Factor Productivity (TFP) Index shown in Figure 1 are derived from the product of the Technical Efficiency Change (TEC) and Technological Efficiency Change (TC) scores. TEC scores represent the speed at which a decision-making unit (DMU) approaches the efficient production frontier, while TC scores provide information on how much the efficient production frontier has shifted for the DMUs. Pure Efficiency Change (PEC) is considered an indicator of improvements in managerial performance for the DMUs, whereas Scale Efficiency Change (SEC) values reflect the development of the DMUs towards the optimal scale (Färe et al., 1994; Lovell, 1999; Cooper et al., 2007).

In this study, the Malmquist Productivity Index (MPI) model used for analysis is designed based on the works of Zhou et al. (2010) and Pastor et al. (2011). The equations employed in the study are as follows (Lovell, 2003):

In these equations, the values of the efficiency frontier for the first and second time periods, denoted as $(X_0Y_0)^1$ and $(X_0Y_0)^2$ respectively, are defined as follows:

Catch-Up, TEC: $\frac{(X_0Y_0)^2}{(X_0Y_0)^1}$ (1)

Frontier Shift, TC: $\frac{(X_0Y_0)^1}{(X_0Y_0)^2}$ (2)

Malmquist Index (TFPC): TEC X TC (3)

In this study, the role of technological divide on financial and human capital in Turkey's 12 regions during the 2011-2023 period is computed using the Malmquist Productivity Index (MPI). The variables used in the analysis are shown in the table below.

Table 1: Variables Used in the Analysis and Data Sources

	ES	**MD**	**IEO**	**AR-GEH**	**Source**
Inputs	Average years of education by provinces	Distribution of deposits by region	Internet access rate in households according to the Statistical Regional Units Classification	R&D expenditure (TRY) according to the Statistical Regional Units Classification	Data obtained from OECD and World Bank
	AR-GEI	**BUI**	**BCS**	**GINI**	**Source**
Outputs	R&D human resources (Number of people) according to the Statistical Regional Units Classification	Distribution of the number of bank branches by region	Distribution of bank employees by region	Gini coefficient by income	Data obtained from OECD and World Bank

Table 1 defines the variables included in the analysis to investigate the effects of four inputs (ES, MD, IEO, AR-GEH) on four outputs (AR-GEI, BUI, BCS, GINI). The inputs represent indicators of resources or development levels in Turkey's regions, while the outputs measure the socio-economic impacts of these resources. The inputs and outputs in Table 1 are explained in light of similar studies in the literature.

This study develops a regional model of economic and social performance based on a production-process perspective. The selected inputs represent the key structural factors that determine regional development - human capital, financial capacity, digital infrastructure, and innovation potential - while the outputs capture the direct and indirect outcomes generated by these inputs.

Inputs:

Average Education Duration by Province (ES): Represents the stock of human capital in each region. Longer education durations indicate a more skilled labor force and higher knowledge accumulation (Manca, 2012).

Deposit Distribution by Region (MD): Serves as an indicator of financial depth and economic well-being. Higher deposit levels imply stronger savings and investment potential (Jeanneney & Kpodar, 2011; Omar & Inaba, 2020).

Internet Access Rate (IEO): Reflects the technological infrastructure that facilitates knowledge diffusion, digital services, and innovation activities (George & Prabhu, 2003).

R&D Expenditures (AR-GEH): Represent investments in innovation and technology that enhance long-term productivity and regional competitiveness (Bilbao-Osorio & Rodríguez-Pose, 2004; Inekwe, 2015).

Outputs:

R&D Human Resources (AR-GEI): A direct outcome of education (ES), R&D expenditure (AR-GEH), and digital infrastructure (IEO). Higher educational attainment and R&D investment foster the development of skilled researchers and innovation capacity (Teixeira & Fortuna, 2010; Sánchez-Sellero & Bataineh, 2022).

Number of Bank Branches (BUI): A tangible output of financial and technological inputs. Deposit accumulation (MD) and digitalization (IEO) encourage the expansion of financial infrastructure across regions (Czernich et al., 2011; D'Andrea & Limodio, 2024).

Distribution of Bank Employees by Region (BCS): Represents the labor-intensive dimension of financial activity. Regions with greater deposit volumes and higher education levels tend to employ more financial service workers (Ansong et al., 2015).

Gini Coefficient by Income (GINI): The ultimate social outcome of the model. Rather than a direct production output, GINI captures the distributive effects of the economic and financial outputs, reflecting how innovation and financial inclusion influence income equality (Lambert, 1985; Catalano et al., 2009; Luptáčik & Nežinský, 2020).

3.1. Ethical Permissions fort he Research

This study adhered to all regulations outlined in the "Drictive on Scientific Research and Publication Ethics of Higher Education Institutions". No actions listed under the second section of the Directive, titled "Actions Contrary to Scientific Research and Publication Ethics" were undertaken.

4. FINDINGS

This study aims to examine the determinants of changes in total factor productivity (TFP) in the context of the Digital Divide Theory, focusing on the effects of technological disparity on financial and human capital across 12 regions of Turkey during the period 2011–2023. For this purpose, the Malmquist Index

(MI) is employed to conduct a comparative analysis of TFP among the regions. The empirical findings obtained through the analysis are presented in detail below:

Table 2: Correlation Matrix of Variables

Variables	ES	MD	IEO	AR-GEH	AR-GEI	BUI	BCS	GINI
ES	1	0.457**	0.065	-0.156	-0.340*	0.368*	-0.215	0.205
MD	0.457**	1	0.439**	-0.084	0.016	0.193	-0.148	0.031
IEO	0.065	0.439**	1	0.588***	-0.475**	0.191	0.319*	0.402**
AR-GEH	-0.156	-0.084	0.588***	1	-0.424**	0.294*	0.629***	0.424**
AR-GEI	-0.340*	0.016	-0.475**	-0.424**	1	-0.318*	-0.219	-0.383*
BUI	0.368*	0.193	0.191	0.294*	-0.318*	1	-0.002	0.908***
BCS	-0.215	-0.148	0.319*	0.629***	-0.219	-0.002	1	0.188
GINI	0.205	0.031	0.402**	0.424**	-0.383*	0.908***	0.188	1

Notes: * p <0.1; ** p <0.05; *** p < 0.01

In Table 2, there is a weak but positive relationship between the average years of education by province (ES) and the distribution of deposits by region (MD). This suggests that as the level of education increases, there is a tendency for deposit accumulation to increase as well. A moderate positive relationship is found between the average years of education and the number of bank branches (BUI), while a negative relationship is observed with R&D human resources (AR-GEI). This indicates that while the level of education is related to economic activities, a longer education period does not directly increase the human resources for R&D. As shown in Table 2, some correlations revealed unexpected directions. In particular, the negative correlation between R&D expenditure and R&D human resources (-0.424) may reflect regional differences in the nature of R&D investments, where some regions exhibit more capital-intensive rather than labor-intensive activities. Similarly, the negative association between internet access and R&D human resources (-0.475) could be a result of such structural variations or temporal discrepancies within the dataset. This suggests that the relationships among R&D indicators may not be strictly contemporaneous but shaped by indirect and temporal Dynamics.

Table 2 presents the correlation coefficients among the study variables, along with their statistical significance levels. Several correlations were found to be statistically significant at conventional thresholds (p <0.1, p <0.05, and p <0.01). For instance, the positive association between internet access (IEO) and R&D human resources (AR-GEH) is strong and highly significant (r = 0.588, p

<0.01), whereas the negative relationships between R&D expenditure and R&D human resources ($r = -0.424$, $p < 0.05$) and between R&D expenditure and internet access ($r = -0.475$, $p < 0.05$) are also statistically meaningful. These results indicate that the correlations observed are not random but reflect systematic patterns across regions, warranting further interpretation in the Discussion section.

A positive and moderate relationship is observed between the distribution of deposits by region (MD) and the internet access rate in households according to the Statistical Regional Units Classification (IEO). This indicates that deposit accumulation in regions is directly proportional to the internet access rate. On the other hand, there is a weak but positive relationship between MD and the number of bank branches by region (BUI), suggesting that deposit accumulation partially increases the number of bank branches.

A strong and positive relationship is found between internet access rate (IEO) and R&D expenditure (AR-GEH). Internet access is seen as an important factor for increasing R&D spending. However, a negative relationship is found between IEO and R&D human resources (AR-GEI), suggesting that increased internet access tends to reduce the demand for R&D human resources.

A strong and positive relationship is identified between R&D expenditure (AR-GEH) and the distribution of bank employees by region (BCS). This suggests that an increase in R&D spending may lead to a rise in the distribution of bank employees. A moderate positive relationship is found between AR-GEH and the Gini coefficient (GINI), indicating that R&D expenditure has a positive impact on income inequality.

A weak negative relationship is found between R&D human resources (AR-GEI) and the number of bank branches by region (BUI). A weak negative relationship is also observed between AR-GEI and GINI. This suggests that as R&D human resources increase, income inequality is likely to decrease. On the other hand, a very strong positive relationship is found between BUI and GINI, showing a strong connection between the number of bank branches and income inequality.

Table 3: Technical Efficiency Change (TEC) Scores by Region

Catch-up	2011=>2012	2012=>2013	2013=>2014	2014=>2015	2015=>2016	2016=>2017	2017=>2018	2018=>2019	2019=>2020	2020=>2021	2021=>2022	2022=>2023	Average
Istanbul	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Western Marmara	1.002	1.101	0.957	1.045	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.009
Aegean	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Eastern Marmara	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Western Anatolia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Mediterranean	1.000	1.000	1.000	0.423	1.000	1.365	1.007	1.000	1.336	1.000	1.124	1.000	1.022
Central Anatolia	1.030	1.061	0.758	0.909	1.452	0.710	1.265	1.113	0.994	0.506	0.944	1.104	0.987
Western Black Sea	1.000	1.000	1.000	1.000	0.626	1.598	1.000	1.000	1.000	1.000	1.000	1.000	1.019
Eastern Black Sea	0.974	1.285	0.699	1.043	1.330	0.735	1.117	1.119	0.785	0.977	1.032	1.051	1.012
Northeast Anatolia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Middle East Anatolia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Southeast Anatolia	1.000	1.000	1.000	1.000	1.000	0.865	1.000	1.124	1.028	1.000	0.998	0.921	0.995
Average	1.001	1.037	0.951	1.000	0.986	1.023	1.032	1.030	0.984	0.957	0.998	1.006	1.007

Periods where TEC> 1 indicate that regions have accelerated their approach to the production frontier by reducing idle input use and minimizing resource waste. Conversely, TEC <1 reflects a slowdown in this process. As shown in Table 3, the average TEC across Turkey increased by about 1%, with Western Marmara, Mediterranean, Western Black Sea, and Eastern Black Sea exceeding 1.0, indicating notable efficiency improvements.

In regions such as Istanbul, Aegean, Eastern Marmara, Western Anatolia, Northeast Anatolia, and Middle East Anatolia, TEC values remained stable, suggesting these areas were already close to the efficient frontier. Western Marmara experienced a 10.1% rise in 2012–2013 but faced a 14.4% decline in the following year, later recovering to an overall average of 1.009, showing a generally positive trend.

In the Mediterranean, TEC dropped sharply by 58% in 2015–2016 but rebounded by 36.5% the next year, achieving the highest regional average (1.022) in approaching the production frontier. Central Anatolia showed fluctuating results, with a 45.2% rise in 2015-2016 but an overall average of 0.987, indicating a slight efficiency decline. Eastern Black Sea recorded a 25.5% surge in 2012-2013 and ended the period with a modest 1.2% improvement overall.

Finally, Southeastern Anatolia displayed variable performance as well; despite a 13.5% decrease (TEC = 0.865) in 2016-2017, its period average of 0.995 indicates that the region remained close to the efficient production frontier.

Table 4: Technological Efficiency Change (TC) Scores of Regions

Frontier	2011=>2012	2012=>2013	2013=>2014	2014=>2015	2015=>2016	2016=>2017	2017=>2018	2018=>2019	2019=>2020	2020=>2021	2021=>2022	2022=>2023	Average
Istanbul	1.237	1.111	1.075	1.101	1.051	0.847	0.972	1.165	1.000	0.980	1.039	0.987	1.047
Western Marmara	0.947	0.983	0.944	0.823	0.014	1.164	1.012	0.957	0.905	1.139	1.010	1.057	0.913
Aegean	0.944	1.010	1.242	1.097	1.134	0.722	0.581	1.075	1.400	0.849	0.981	0.983	1.001
Eastern Marmara	1.089	1.157	0.754	0.997	0.910	0.915	1.113	0.713	0.862	0.952	1.183	0.904	0.962
Western Anatolia	0.970	0.936	1.144	1.115	1.000	1.000	0.895	0.919	1.000	1.000	1.100	0.922	1.000
Mediterranean	0.765	0.776	0.981	0.988	0.910	1.000	1.019	0.999	1.000	0.978	0.959	1.000	0.940
Central Anatolia	0.834	0.973	1.138	0.910	0.997	1.080	0.819	0.954	1.079	1.084	0.979	0.991	0.987
Western Black Sea	0.827	1.109	1.030	0.847	0.711	0.964	0.906	1.013	1.000	0.885	0.522	0.849	0.888
Eastern Black Sea	0.960	1.013	1.014	0.862	0.810	1.000	0.905	0.590	0.987	1.070	0.985	0.969	0.930
Northeast Anatolia	1.000	0.769	0.916	0.952	0.957	1.000	0.963	0.969	1.000	1.000	1.000	0.990	0.960
Middle East Anatolia	1.000	0.990	1.000	1.000	1.000	1.000	0.980	1.000	1.000	1.000	1.000	0.996	0.997
Southeast Anatolia	0.873	0.804	0.867	0.790	0.757	1.000	0.830	0.877	0.902	0.977	0.950	0.848	0.873
Average	0.954	0.969	1.009	0.957	0.854	0.974	0.916	0.936	1.011	0.993	0.976	0.958	0.958

The TC value provides important insights into the level of technological adaptation and the use of digital transformation by decision-making units (DMUs). Additionally, the TC value offers information on the direction and magnitude of changes in the efficient production frontier for DMUs. Based on this information, technological transformation projections can be determined for each DMU. For DMUs with TC>1, there is an increase in technological efficiency, indicating an upward shift in the production frontier. Conversely, for DMUs with TC<1, there is a decrease in technological efficiency, signifying a downward shift from the production frontier. For DMUs with TC = 1, it is indicated that there is stability in technological efficiency.

Table 4 presents the technological efficiency change scores for Turkey's regions from 2011 to 2023. These scores reflect the regions' proximity to the production frontier and the changes in technological efficiency over the periods. Table 4 reveals that Istanbul (1.047) and the Aegean Region (1.001) were the only regions with an average TC above 1, suggesting relatively higher technological progress on average. Nevertheless, both regions also exhibited periods of technological regress (TC <1), implying fluctuations in innovation efficiency and the non-linear nature of their technological development. Additionally, the Western Anatolia Region achieved a score of "1". A total of 8 DMUs were calculated with TC <1, with the Southeastern Anatolia Region experiencing the most significant loss in technological efficiency, with a score of 0.873.

Looking at the Eastern Marmara region in Table 4, a significant increase of 15.7% in technological efficiency during the 2012-2013 period indicates an upward shift in technological efficiency. However, the 28.7% decrease in the 2018-2019 period highlights the significance of the technological efficiency loss in the region. As a result, Eastern Marmara displayed relatively stagnant performance over the period, with an average TC decrease of 3.8%. A similar trend is observed in the Northeastern Anatolia region, where a 4% average decrease in TC was recorded.

According to Table 4, the average TC scores over the analyzed years were calculated as "0.958", which is below the value of "1". This indicates that, overall, Turkey's regions experienced a slight downward shift in technological efficiency across the production frontier. Furthermore, according to the table, the period from 2019 to 2020 saw the highest increase in technological efficiency, with an average growth of 1.1%. In contrast, the period from 2015 to 2016 experienced the highest decrease in technological efficiency, with an average loss of 14.6%.

Table 5: Total Factor Productivity Change Scores of Regions

Malmquist	2011=>2012	2012=>2013	2013=>2014	2014=>2015	2015=>2016	2016=>2017	2017=>2018	2018=>2019	2019=>2020	2020=>2021	2021=>2022	2022=>2023	Average
Istanbul	1.237	1.111	1.075	1.101	1.051	0.847	0.972	1.165	1.000	0.980	1.039	0.987	1.047
Western Marmara	0.948	1.083	0.904	0.860	0.014	1.164	1.012	0.957	0.905	1.139	1.010	1.057	0.921
Aegean	0.944	1.010	1.242	1.097	1.134	0.722	0.581	1.075	1.400	0.849	0.981	0.983	1.001
Eastern Marmara	1.089	1.157	0.754	0.997	0.910	0.915	1.113	0.713	0.862	0.952	1.183	0.904	0.962
Western Anatolia	0.970	0.936	1.144	1.115	1.000	1.000	0.895	0.919	1.000	1.000	1.100	0.922	1.000
Mediterranean	0.765	0.776	0.981	0.988	0.910	1.365	1.026	0.999	1.000	0.978	0.959	1.000	1.002
Central Anatolia	0.860	1.033	0.862	0.828	1.447	0.767	1.036	1.062	1.072	0.549	0.925	1.094	0.974
Western Black Sea	0.827	1.109	1.030	0.847	0.445	1.540	0.906	1.013	1.000	0.885	0.522	0.849	0.905
Eastern Black Sea	0.935	1.301	0.709	0.900	1.078	0.735	1.011	0.660	0.775	1.045	1.017	1.018	0.942
Northeast Anatolia	1.000	0.769	0.916	0.952	0.957	1.000	0.963	0.969	1.000	1.000	1.000	0.990	0.960
Middle East Anatolia	1.000	0.990	1.000	1.000	1.000	1.000	0.980	1.000	1.000	1.000	1.000	0.996	0.997
Southeast Anatolia	0.873	0.804	0.867	0.790	0.757	0.865	0.830	0.986	0.927	0.977	0.948	0.781	0.868
Average	0.954	1.007	0.957	0.956	0.848	0.993	0.944	0.960	0.995	0.946	0.974	0.965	0.965

The Total Factor Productivity Change (TFPC), calculated as the product of TEC and TC, offers valuable insights into the productivity performance of Decision-Making Units (DMUs) over time. When TFPC> 1, it indicates that regions have improved both their convergence speed to the efficient frontier and their ability to utilize technological progress effectively. Conversely, TFPC <1 reflects productivity losses, which may result from inefficiencies in TEC, TC, or both. Identifying the main source of this decline is crucial for designing targeted policy interventions (Cooper et al., 2007).

As shown in Table 5, the average TFPC value across Turkey's regions is 0.965, implying an overall 3.5% productivity loss during the period. A regional breakdown reveals that Istanbul, Aegean, and Mediterranean achieved productivity gains, with Istanbul recording the highest score (1.047) due to its strong technological transformation capacity. The Mediterranean's improvement stems primarily from gains in TEC, while the Aegean's increase is linked to advancements in TC.

Western Anatolia maintained a stable productivity level with an average score close to 1.000, despite fluctuations after a notable 14.4% rise in 2013-2014. Similarly, Middle East Anatolia remained efficient on average (0.997), consistently recording near-unity values except for a few periods (2012-2013, 2017-2018, and 2022-2023).

Across all regions, the 2012-2013 period stands out with the highest productivity gain (+0.7%), whereas 2015-2016 shows a sharp decline (-15.2%), possibly reflecting internal or external economic shocks. The MI results for 2011-2023 are presented as average scores and graphical representations in the following section.

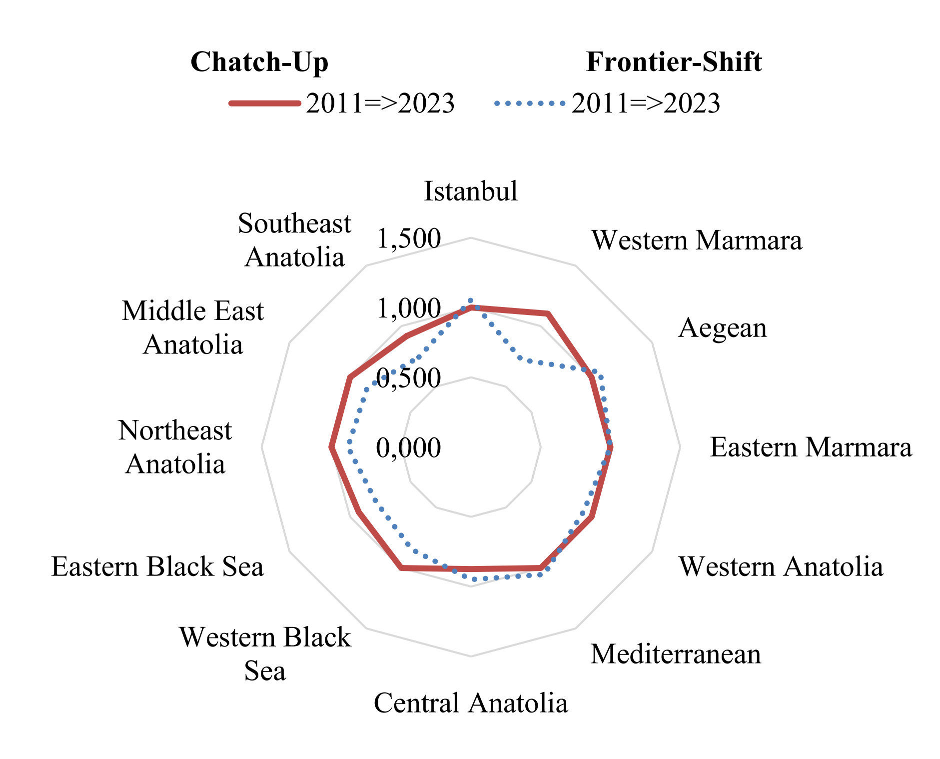

Figure 2: Catch-Up and Frontier-Shift Scores (2011-2023)

Figure 2 illustrates the regional dynamics of efficiency change ("catch-up") and technological change ("frontier-shift") between 2011 and 2023. In these radar charts, values plotted closer to the center indicate lower efficiency or technological performance (TC <1), whereas points farther from the center indicate relative improvement (TC> 1). The catch-up panel shows that most regions maintained stable efficiency levels close to 1.0, implying limited convergence toward the efficiency frontier. In contrast, the frontier-shift panel reveals greater variation across regions, suggesting that technological progress rather than pure efficiency gains has been the main driver of productivity change. Istanbul (1.054) and the Mediterranean region (1.055) display the highest frontier-shift scores, reflecting their stronger innovation dynamics and ability to push the technology frontier forward.

According to Figure 2, Istanbul and Western Marmara are the leaders in catch-up performance, adapting more quickly to productivity-enhancing practices compared to other regions. Furthermore, in terms of frontier-shift performance, Istanbul, Aegean, and Mediterranean regions are identified as pioneers in adapting to technological innovations relative to the other regions. On the other hand, the relatively low performance in catch-up for Central Anatolia and Southeastern Anatolia is noteworthy, indicating significant difficulties in closing the gap between these regions and the efficient production frontier. In terms of frontier-shift performance, however, it is evident that the efficient production frontier has significantly shifted downward in the Southeastern Anatolia, Eastern Black Sea, and Western Black Sea regions.

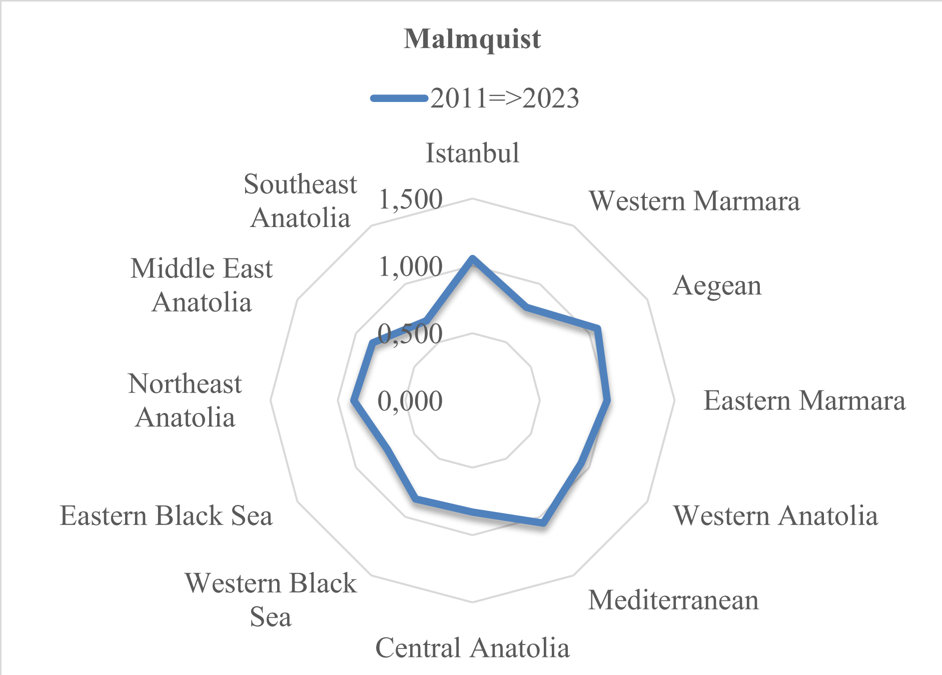

Figure 3: Malmquist TFP Scores (2011-2023)

Figure 3 presents the Malmquist total factor productivity (TFP) index, which combines both the catch-up and frontier-shift components. Similar to Figure 2, values closer to the center indicate a decline in total productivity (TFP <1), while outer values above 1 indicate productivity improvement. Istanbul (1.054) and the Aegean (1.072) regions exhibit the highest average TFP gains over the period, highlighting their relatively stronger technological capabilities. However, several regions-particularly those in Eastern and Southeastern Anatolia-display scores below 1, implying technological regress and persistent productivity gaps relative to the national frontier. Overall, the radar pattern suggests that regional productivity growth in Turkey has been uneven, driven primarily by a few innovation-intensive regions.

In the radar chart, the innermost circle represents the least efficient DMUs, while the outermost circle represents the efficient production frontier. DMUs located closer to the center are considered inefficient, while those positioned at the middle or closer to the outermost circle are considered efficient.

According to Figure 3, the regions of Istanbul, Aegean, and Mediterranean are located on the efficient production frontier line in terms of

TFP, indicating their efficiency. On the other hand, the regions with the lowest scores and farthest from the efficient production frontier are Southeast Anatolia and Eastern Black Sea. These regions have experienced significant declines in productivity. The radar chart also highlights that Eastern Marmara and Western Anatolia are situated near the efficient production frontier, suggesting that productivity improvements are more easily achievable in these regions compared to others.

In line with H_1, the findings confirm that regional differences in financial and human capital significantly explain variations in total factor productivity (TFP) within the framework of the Digital Divide Theory. Regions with higher financial depth-measured through deposit distribution (MD)-and greater human capital accumulation-represented by average years of education (ES)-displayed superior productivity outcomes. Particularly, Istanbul, the Aegean, and the Mediterranean regions, which combine strong financial infrastructures and well-developed educational profiles, achieved higher technical and total factor productivity scores. Conversely, Eastern and Southeastern Anatolia, characterized by lower human and financial capital accumulation, recorded weaker efficiency and productivity performance. These results verify that disparities in capital endowments are a primary determinant of regional productivity differences.

Findings related to H_2 also support the hypothesis that regions with higher levels of digitalization and R&D-based human capital accumulation experience stronger TFP growth. Regions such as Istanbul, the Aegean, and the Mediterranean, where internet access and R&D human resources (AR-GEI) are more advanced, exhibited TFPC values above 1, reflecting both technological progress (TC>1) and efficiency gains (TEC>1). This demonstrates that the combined effect of digital connectivity and innovation-oriented human capital significantly enhances regional productivity, reinforcing the role of digital transformation as a key driver of growth.

Regarding H_3, the results reveal that the effects of the technological divide on productivity vary substantially across development levels, confirming the asymmetric nature of digitalization’s impact. While developed and innovation-intensive regions benefited from technological diffusion and frontier expansion, lagging regions such as Southeastern and Eastern Anatolia remained below the efficiency frontier, indicating limited absorptive capacity and structural constraints. Thus, although digitalization contributes positively to productivity overall, its impact is non-uniform and strongly dependent on regional development capacity, institutional readiness, and the efficiency of human capital utilization.

5. CONCLUSION AND EVALUATION

This study investigates the determinants of Total Factor Productivity (TFP) changes in Turkey's regions between 2011 and 2023, focusing on the roles of financial and human capital within the context of technological disparities. The findings derived from the Malmquist Index (MI) analysis-conducted with eight selected variables (four inputs and four outputs)-are presented in detail through tables and graphs. Based on these results, comparative inferences are drawn across Decision-Making Units (DMUs), and policy recommendations are proposed. The study particularly emphasizes the productivity differences between rural and urban regions.

The Technical Efficiency Change (TEC) results show that Western Marmara, Mediterranean, Western Black Sea, and Eastern Black Sea recorded scores above "1," indicating faster convergence toward the efficient production frontier. Meanwhile, the Technological Change (TC) scores highlight Istanbul and the Aegean Region as the only areas with TC> 1, reflecting enhanced technological utilization capacity. Over the entire period, Istanbul and Western Marmara achieved the highest improvements in catching up with the efficiency frontier, while Istanbul, Aegean, and Mediterranean regions exhibited the strongest technological progress.

These findings demonstrate that TEC-representing reductions in resource waste and idle input use-and TC-reflecting technological advancement-highlight different regional strengths. Therefore, regional strategies for technological transformation should balance investments in financial capital and human resource development to ensure both efficiency and innovation gains.

Regarding Total Factor Productivity Change (TFPC), both annual and overall results indicate that Istanbul, Aegean, and Mediterranean regions achieved the strongest productivity growth, whereas Southeast Anatolia and Eastern Black Sea consistently lagged behind. These findings are consistent with prior studies such as Majeed and Ayub (2018), which confirm that digitalization and R&D-related activities contribute positively to regional productivity and competitiveness.

In regions like Eastern Marmara, where TFP performance fluctuated across years, suboptimal technological infrastructure, education, and financial capacity appear to limit growth. For these regions, optimizing production scale and enhancing managerial efficiency are crucial. In contrast, in Central and Eastern Anatolia, rising R&D human capital and declining income inequality have been associated with steady improvements in technological efficiency and TFP. These results suggest that sustained investments in R&D-oriented human capital can gradually close productivity gaps in less-developed areas.

Another important finding concerns the relationship between income inequality and technological inefficiency in high-deposit regions. In Istanbul and Eastern Marmara, where banking sector indicators (BUI and BCS) increased, technological inefficiency emerged as a key obstacle to technical efficiency. Therefore, policy frameworks aimed at reducing income inequality-particularly through targeted R&D investments and human capital strengthening-should be prioritized.

Finally, the analysis reveals that rural regions consistently recorded TFP scores below “1,” indicating persistent productivity gaps relative to urban areas. Urban regions, by contrast, benefited more from the synergistic effects of financial and human capital in driving technological progress. These results align with previous research, including Jiménez et al. (2014) and Nair et al. (2020), reinforcing the critical role of digitalization and inclusive investment in promoting regional productivity convergence.

When interpreted through the lens of the Digital Divide Theory, the empirical results suggest that disparities in access to technology, human capital, and digital infrastructure remain critical determinants of productivity performance across Turkey’s regions. The Digital Divide Theory posits that unequal access to digital and technological resources leads to divergent development paths, particularly between urban and rural areas. In line with this framework, our results demonstrate that regions with higher levels of digital connectivity and R&D human capital-such as Istanbul, the Aegean, and the Mediterranean-consistently achieve superior productivity outcomes, while peripheral and rural regions continue to experience technological lag.

The unexpectedly negative correlations observed in Table 2 (e.g., between R&D expenditure and R&D human resources, or between internet access and R&D human resources) may reflect structural differences between capital-intensive and labor-intensive investment patterns or potential time lags in data. Similar paradoxical findings have been discussed in prior empirical studies, including those by Czernich at al. (2011) and Kostyaev (2024), which emphasize that the benefits of R&D investments often manifest with delay and depend on institutional capacity and absorptive efficiency. Thus, the observed negative associations should not be interpreted as contradictions but rather as reflections of transitional phases in regional innovation systems.

Moreover, the regional heterogeneity highlighted by the MI results aligns with broader literature emphasizing non-linear and path-dependent technological development (Li & Liu, 2010; Pastor et al., 2011). Developed regions benefit from cumulative innovation effects, while lagging regions face structural constraints that limit the translation of financial and R&D inputs into productivity outcomes. Therefore, policies aiming to bridge Turkey's technological divide should focus not only on expanding R&D expenditure but also on enhancing its efficiency and alignment with human capital and digital readiness.

Based on these findings, tailored development strategies should be designed and implemented for low-productivity rural regions, taking into account their specific strengths and capacities. Investments in digital infrastructure and technology access should be scaled up, while mechanisms for information and technology transfer-from high-productivity urban regions such as Istanbul and Western Marmara to lagging regions-should be established. Furthermore, encouraging collaboration between universities, industries, and public institutions could enhance knowledge diffusion and accelerate regional technological convergence.

Ultimately, the study underscores that reducing the technological divide requires not only financial investment but also strategic coordination of human capital, institutional capability, and regional innovation systems. Integrating these dimensions is essential to achieving sustainable productivity growth and balanced regional development in Turkey.

Finally, this study acknowledges certain limitations. While it provides valuable insights into the relationship between digitalization, human capital, and regional productivity, the analysis relies on regional-level secondary data, which may overlook firm-level dynamics and micro-scale innovation effects. In addition, the use of annual data may not fully capture the time lags between R&D investments and productivity outcomes, and the Malmquist Index approach, though robust, does not account for institutional or policy factors affecting efficiency. Future research could address these limitations by employing micro-level or panel data models, incorporating institutional variables, and conducting cross-country comparisons to better understand how digital divides shape productivity across different economic contexts.

6. CONFLICT OF INTEREST STATEMENT

There is no conflict of interest between the authors.

7. FINANCIAL SUPPORT

This study did not benefit from any funding or support.

8. AUTHOR CONTRIBUTIONS

RT, İA: Idea;
RT: Design;
RT, İA: Supervision;

RT, İA: Collection and/or processing of resources;
RT: Analysis and/or interpretation;
İA: Literature review;
RT, İA: Author of the article;
RT, İA: Critical review

9. ETHICS COMMITTEE STATEMENT AND INTELLECTUAL PROPERTY COPYRIGHTS

The study adhered to the ethics committee's principles, and necessary permissions were obtained in accordance with intellectual property and copyright regulations.

10. USE OF ARTIFICIAL INTELLIGENCE (AI) TOOLS

Artificial intelligence tools were used solely for language editing and improvement of clarity in this study. The authors confirm that AI tools did not contribute to the study design, data analysis, interpretation of results, or the generation of scientific content.

11. DATA AVAILABILITY

The dataset used in this study is publicly available and is explained in detail within the manuscript. No restrictions apply to the access of the data.

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