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DIGITAL DISTANCE AND TRADE DYNAMICS: THRESHOLD EFFECTS ON TURKIYE'S EXPORT PERFORMANCE

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Abstract: This study investigates whether digital distance—defined as disparities in digital and technological capabilities between countries—constitutes a critical determinant of Turkey's export performance in the evolving architecture of international trade. Moving beyond traditional gravity-based explanations centered on geographical distance, the article develops a multidimensional digital distance index derived from the Frontier Technological Readiness Index (FTRI) and the Economic Complexity Index (ECI). Using annual panel data for 108 trading partners over the period 2008–2022, the analysis integrates GDP and exchange-rate controls within a panel threshold regression framework, complemented by panel causality tests. The findings reveal a statistically significant single-threshold structure, demonstrating that digital distance exerts nonlinear and asymmetric effects on Turkey's exports. While convergence in ICT infrastructure and financial access tends to enhance export performance, narrowing gaps in certain dimensions—particularly skills and R&D—does not uniformly yield positive trade outcomes. In fact, larger disparities in selected technological capabilities may generate temporary competitive advantages, consistent with technology-gap theory. Robustness checks incorporating economic complexity distance confirm these threshold dynamics. Moreover, causality results indicate predominantly bidirectional relationships between exports and digital dimensions, underscoring mutual reinforcement between trade and digital transformation. Overall, the results challenge the presumption that digital

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convergence universally promotes trade. Instead, they highlight the strategic importance of selective digital specialization and innovation-driven competitiveness. By conceptualizing and empirically validating digital distance as a structural trade determinant, the study contributes to the emerging literature on digitalization and international trade and offers policy insights for adaptive, data-driven export strategies in an era of technological disruption.

Keywords: Digital distance, export performance, frontier technological readiness index (FTRI), economic complexity index (ECI), panel threshold regression.

JEL: F10, O32, O33

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Introduction

Recent advancements in trade, logistics, finance and the economy raise the question if the struggles or achievements in these fields are deriving from a geographical distance or are the result of a “digital distance”. Historically, not only goods but also technologies are transferred through trade routes (Christian, 2000: 5). The effect of digitalization can be categorized as structural and competitional (Ahmedov, 2020).

Distance is also an obstacle to tackle in trade. Huang (2007) states that trade volumes with distant partners are not as high as the ones that are closer. The low volumes have been analyzed considering the effects of transportation costs (Obstfeld & Rogoff, 2000), obstacles in flow of capital, and informational barriers (Rangan & Lawrence, 1999). In a digitalized economy, discussions on the subject can be shifted towards the level of digitalization, in other words, how trade partners can be seen very close geographically but enormously distant digitally. To visualize this phenomena, Figure 1 illustrates the Differences from Turkey in Economic Complexity Index (ECI) by The Observatory of Economic Complexity and Frontier Technological Readiness Index (FTRI) by UN Trade and Development (UNCTAD).

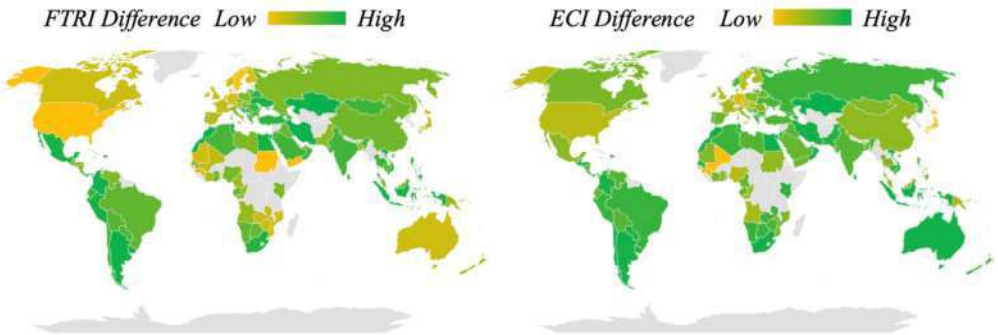

Figure 1. ECI and FTRI differences from Turkey

In Figure 1, those that are closest to Turkey are shown in green and the furthest ones are represented in yellow. The figure helps understanding how economically close countries can in fact be digitally distant. For instance, some Balkan countries seem to be not differing from Turkey at an economic development level. At the same time, the same countries change color to a more yellowish tone in terms of differences from Turkey in readiness to frontier technologies. The intuitive results correspond to the aim of this study in investigating the results of digital distance between Turkey and its trade partners and effects on international trade.

The new era of digitalization brings new challenges to international trade. In regard to studies such as Cermeno and Vazquez (2009), technological capabilities are linked to activities in R&D, human capital, openness and investment levels. Since these capabilities are highly related to bilateral trade flows as stated by Esfahani and Tayebi (2016), some certain digital distances may affect exports more than others both positively and negatively. Hence, this research contributes to the literature by analyzing how digital distance can be a major performance issue between trade partners. This research also aims to determine the impact of digital distance on Turkey's export dynamics, and reveal its implications on trade competitiveness and economic policies.

1. Literature Review

1.1. Historical View

The impact of technological differences on *trade* between economies, nations, firms and even sectors has been an important research topic for decades. As technological innovations have accelerated as a result of the Industry 4.0 revolution, recent publications have focused on *digitalization* in *trade* activities. While the subject was explained with the *technological gap* in the early 1980s, today we view the emergence of the concept of *digital distance* between countries. Not limited to these, many terms have been added to the literature over time, such as *technological level, technological distance, digital gap, digital divide and digitalization level.* Figure 2 illustrates how frequently these concepts have been used in publications over time. The dataset was extracted from Web of Science (WOS) database by searching the key words "*technological gap" and "trade"; "technological level" and "trade"; "technological distance" and "trade"; "digital gap" and "trade";*

"digitalization level" and "trade"; "digital distance" and "trade"; "digital divide" and "trade"; "digitalization" and "trade"; "digital technology" and "trade". The publication period covers the period until October 04, 2025. The search field of *TOPIC* has been selected.

It is viewed that the concept of technological gap has still been examined since 1981, although a new concept of digital gap emerged after the 2000s. Moreover, the concept of technological level has been analyzed since the early 1990s, the number of studies has increased over time, and it still stays popular even today. Moreover, after 2019, the concept of digitalization level began to appear in literature. In addition to this, it was noticed that the concept of digital divide was also widely studied as of 2001. Contrary to this, a new concept, digital distance, was limitedly studied in 2024 and 2025.

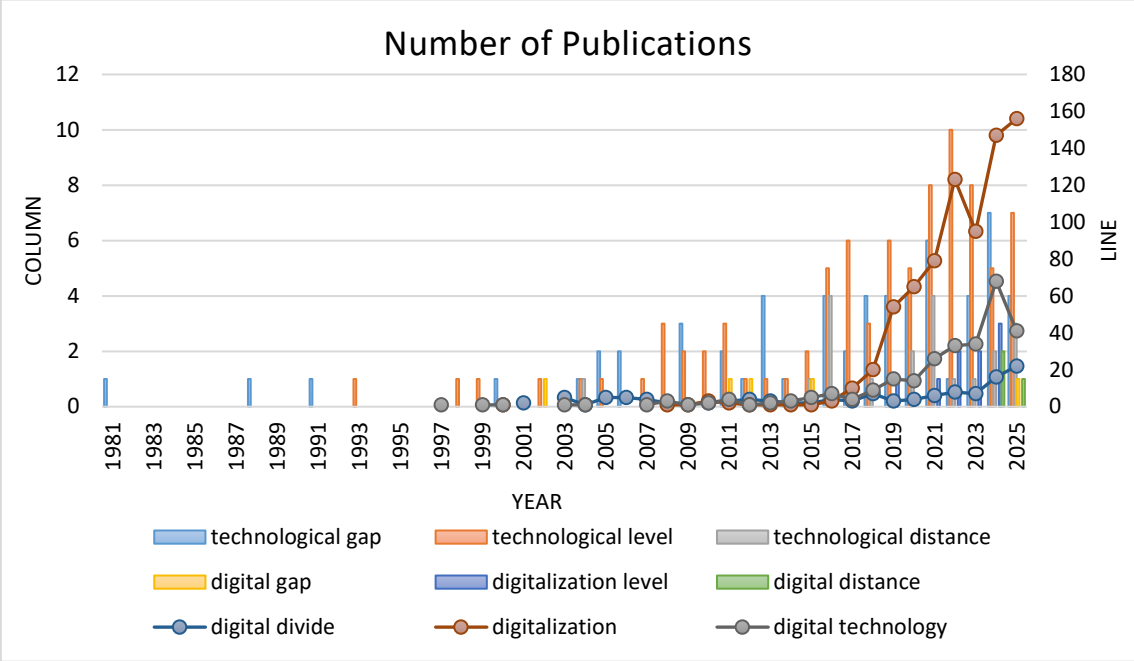

Figure 2. Number of publications related to concepts by year
Source: Prepared by authors based on data extracted from WOS database, 2025

Particularly, since the 2000s, digitalization and related concepts have been studied more frequently in literature and there has been a significant increase in the number of publications today. More than 750 publications related to digitalization and trade have been yielded since 2000. Findings show that publications on the related subjects have increased significantly since 2018, and their number nearly doubled after 2021.

1.2. Conceptual View

Posner's (1961) technology-gap framework suggests that when technological progress occurs unevenly across countries—affecting certain industries but not others—temporary advantages arise that can generate trade until innovations diffuse or are imitated abroad, thereby altering relative production costs. Building on this idea, Soete (1981) empirically evaluates the technology-gap hypothesis and shows that innovation across a broad set of industries plays a decisive role in shaping international trade patterns. Antimiani and Costantini (2013) further demonstrate that the European Union's enlargement narrowed technological disparities between existing and new member states, with particularly strong export gains for newcomers and technology-intensive sectors. Cermeño and Vazquez (2009) report that the agricultural technology gap between developed and developing economies widened from 1961 to 1991, noting that technological capabilities are closely linked to human capital, R&D activity, openness, and investment levels, even if this relationship does not always hold for every individual group. Hawash and Lang (2020) examine ICT adoption and its influence on total factor productivity, finding that although digital disparities matter, reducing them alone is insufficient to generate substantial productivity improvements. Dung (2024) argues that trade liberalization can actively reshape the technological gap in developing economies by allowing them to import intermediate goods from technologically advanced partners. Additional empirical work measures technological distance at the firm level (Bar & Leiponen, 2012; Gilsing et al., 2008; Patel & King, 2016), within industries (Vom Stein et al., 2015), and across countries (Fukuchi and Satoh, 1999). Nonetheless, an unresolved question in the literature concerns whether cross-country technological distance ultimately enhances or restricts bilateral trade flows (Esfahani & Tayebi, 2016).

Recent research consistently shows that technological advancement enhances export performance at both the firm and country levels (Ortigueira-Sánchez et al., 2022; Hong and Nam, 2021; Lopez et al., 2022; Marquez-Ramos and Martínez-Zarzoso, 2010; Ozsoy et al., 2022; Asghar et al., 2024). Numerous firm-level studies focus specifically on digital transformation. Denicolai et al. (2021) report that SMEs' international outcomes improve with stronger artificial intelligence capabilities, noting that sustainability and digitalization are mutually reinforcing. Abendin et al. (2022) demonstrate that digitalization significantly strengthens bilateral trade within the Economic Community of West African States. Likewise, Cao and Hsu (2025) use the

Digital Economy and Society Index to show that digitalization mitigates the adverse effects of country differences, helping firms overcome administrative, linguistic, and economic barriers that constrain exports. In contrast, Wang et al. (2024) examine the geographic patterns of emerging digital cross-border mergers and acquisitions and find that greater digital distance between countries can discourage such transactions.

In sum, the studies conducted so far have addressed the concept of technological distance in a narrower scope compared to the concept of digitalization, and the concept of digital distance has been rarely studied with different perspectives. This study differs from the above-mentioned by developing an index to measure how countries' digitalization levels affect bilateral export activities and by proposing a new term, *"digital distance".*

2. Data and Methodology

2.1. Data Specification

Contemporary scholarship underscores that global trade is shaped by multiple determinants, including technological progress (Manickam et al., 2021), economic complexity (Dar et al., 2020; Ajide et al., 2025), exchange-rate movements (Mehtiyev et al., 2021; Kang and Dagli, 2018; Nguse et al., 2021; Asteriou, 2016), and macroeconomic expansion (Nguyen, 2020; Ji et al., 2022; Akhter et al., 2022). In this context, the present study evaluates whether digitalization gaps between Turkey and its trade partners meaningfully influence trade performance, given the centrality of technological capability in advancing sustainable economic development. Focusing on export behavior, the analysis extends recent contributions on technology–trade linkages (Dung, 2024; Cao & Hsu, 2025). The empirical framework employs annual data for 2008–2022 from four databases, incorporating Turkey's bilateral exports, GDP indicators for all countries, exchange rates, the frontier technological readiness index (FTRI), and the economic complexity index (ECI). Table 1 provides variable definitions and econometric specifications.

Table 1
Description and measurement of variables

Variables	Definitions and Measures	Data Source
$Export_{tr}$	Exports of Turkey	Turkey Statistical Institute
GDP_{tr}	Gross Domestic Product of Turkey (Constant 2015 $)	World Bank
GDP_{k}	Gross Domestic Product of Partner Countries (Constant 2015 $)	World Bank
$Exchange_{tr}$	Official Exchange Rate of Turkey (LCU per US$, period average)	World Bank
$Exchange_{k}$	Official exchange rate of Partner Countries (LCU per US$, period average)	World Bank
$DigiD$	Difference of Turkey's FTRI from Partner Country's FTRI	UNCTAD
$DigiD_{ict}$	Difference of Turkey's FTRI sub-index ICT from Partner Country's FTRI sub-index ICT	UNCTAD
$DigiD_{skills}$	Difference of Turkey's FTRI sub-index Skills from Partner Country's FTRI sub-index Skills	UNCTAD
$DigiD_{rd}$	Difference of Turkey's FTRI sub-index Research and Development from Partner Country's FTRI sub-index Research and Development	UNCTAD
$DigiD_{ia}$	Difference of Turkey's FTRI sub-index Industry Activity from Partner Country's FTRI sub-index Industry Activity	UNCTAD
$DigiD_{af}$	Difference of Turkey's FTRI sub-index Access to Finance from Partner Country's FTRI sub-index Access to Finance	UNCTAD
$EciD$	Difference of Turkey's ECI from Partner Country's ECI	The Observatory of Economic Complexity

This study provides valuable insights for policymakers by examining how Turkey's digital distance with its trading partners influences its export performance. The selection of countries includes both developing and developed economies to which Turkey exports, ensuring data availability for the specified period. The primary objective is to assess the impact of digital distance on Turkey's export dynamics, shedding light on its implications for trade competitiveness and economic policy.

2.2. Empirical Model

This research investigates how the digital gap between Turkey and its trade partners functions as a central factor shaping Turkey's export performance. The empirical model includes Turkey's GDP, partner-country GDP, and exchange rates as control variables. While Turkey's GDP reflects domestic production capacity, partner-country GDP captures external demand, and exchange-rate movements jointly influence relative export prices. Although Ozsoy et al. (2022) emphasize that national digitalization significantly explains high-technology export flows, no prior study has incorporated digital distance as an explicit predictor within a comparable econometric setting. Here, digital distance represents the difference in digital advancement between Turkey and its partners; positive values denote Turkey's superior digital capabilities, whereas negative values indicate lagging readiness. Equation 1 includes GDP, exchange-rate, and digital distance variables, and Equations 2–6 extend the model with the UNCTAD (2025) FTRI sub-indices—ICT deployment, skills, R&D activity, industrial capacity, and financial access—alongside the Economic Complexity Index (ECI) to strengthen empirical robustness (Harvard Growth Lab, 2025).

Utilizing these variables, we develop an econometric framework based on equations (1,2,3,4,5,6) to examine the impact of digital distance on export performance:

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{i,t} + \varepsilon \quad (1)$$

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{ict\,i,t} + \varepsilon \quad (2)$$

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{skills\,i,t} + \varepsilon \quad (3)$$

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{rd\,i,t} + \varepsilon \quad (4)$$

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{ia\,i,t} + \varepsilon \quad (5)$$

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 DigiD_{af\,i,t} + \varepsilon \quad (6)$$

Here, *i* and *t* represent country and time, respectively. The stochastic error term is denoted by ε, while the parameters β_1, β_2, β_3, β_4, and β_5 capture

the long-run elasticities of the variables in the equations. Additionally, the model (7) used for robustness checks is presented below.

$$lnExport_{tr_{i,t}} = \beta_0 + \beta_1 lnGDP_{tr_{i,t}} + \beta_2 lnGDP_{k_{i,t}} + \beta_3 lnExchange_{tr_{i,t}} + \beta_4 lnExchange_{k_{i,t}} + \beta_5 EciD_{i,t} + \varepsilon \quad (7)$$

2.3. Panel Threshold Regression

In threshold analysis, selected threshold variables are integrated into the regression framework, based on the premise that explanatory variables affect the outcome variable in a nonlinear manner. Threshold models use a threshold indicator to divide observations into relatively homogeneous regimes, allowing the relationship between variables to shift as the threshold level changes (Li et al., 2020).

Hansen (1999) proposed an estimation technique for balanced panel datasets that incorporates individual effects and identifies structural breaks, enabling the determination of the true threshold value. This approach employs asymptotic distribution and relies on bootstrap procedures to improve inference accuracy. In this study, a panel threshold regression model following Hansen's methodology is applied to assess the nonlinear influence of digital distance on Turkey's export performance (12):

$$e_{it} = \{\alpha_i + \delta' x_{it} + \beta_1 d_{it} + \varepsilon_{it} \quad if \quad d_{it} \leq \gamma \; \alpha_i + \delta' x_{it} + \beta_2 d_{it} + \varepsilon_{it} \quad if \quad d_{it} > \gamma \quad (12)$$

$$\delta = (\delta_1, \delta_2, \delta_3)', \quad x_{it} = (k_{it}, l_{it}, m_{it}, n_{it})'$$

Here, e_{it} denotes Turkey's exports to its trading partners, serving as the dependent variable. The explanatory variable and threshold variable, d_{it}, is represented by DigiD, while γ is the estimated threshold value. In order to control for additional factors that may systematically influence Turkey's exports, four control variables, x_{it}, are included: k_{it} (Turkey's GDP), l_{it} (trading partners' GDP), m_{it} (Turkey's exchange rate), and n_{it} (trading partners' exchange rate). The fixed effect, α_i, accounts for cross-country heterogeneity arising from differences in digitalization levels. The error term, ε_{it}, is assumed to be independently and identically distributed with a mean of zero and finite variance, $\sigma^2(\varepsilon_{it} \sim iid(0, \sigma^2))$. Here, *i* represents trading partner countries, and *t* corresponds to different time periods.

The refined threshold regression model (1) can be reformulated as follows (13):

$$e_{it} = \mu_{it} + \delta' x_{it} + \beta_1 d_{it} I(d_{it} \leq \gamma) + \beta_2 d_{it} I(d_{it} > \gamma) + \varepsilon_{it} \quad (13)$$

Here, I $I(\blacksquare)$ denotes the indicator function. Equation (13) can alternatively be expressed as follows (14):

$$e_{it} = u_i + \delta' x_{it} + \beta' d_{it}(\gamma) + \varepsilon_{it}, \qquad \beta = (\beta_1, \beta_2)' \tag{14}$$

$$e_{it} = \mu_{it} + [\delta', \beta'] \left[\frac{x_{it}}{d_{it}(\gamma)}\right] + \varepsilon_{it}$$

$$e_{it} = \mu_{it} + \omega' d_{it}(\gamma) + \varepsilon_{it}$$

$$d_{it}(\gamma) = \left[\frac{d_{it} I(d_{it} \leq \gamma)}{d_{it} I(d_{it} > \gamma)}\right]$$

Here, $\omega = (\delta', \beta')'$ and $d_{it} = (x'_{it}, d'_{it}(\gamma))'$. The observations are categorized into two distinct regimes based on whether the threshold variable d_{it} is below or above the threshold value (γ). These regimes are characterized by different regression slopes, β_1 and β_2. The parameters ($\gamma, \beta, \delta \; and \; \sigma^2$) are estimated using the known values of e_{it} and d_{it}.

2.4. Panel Threshold Regression

Identifying causal linkages among variables is vital for designing effective policies. To explore these linkages, the study applies the Dumitrescu–Hurlin (2012) panel causality test, which assumes that causal patterns evident in one country may extend to others, with reliability increasing as sample size grows. The associated linear model is shown in Equation 15:

$$Y_{it} = \beta_i + \sum_{j-1}^{J} \delta_i^j Y_{i(t-j)} + \sum_{j-1}^{J} \eta_i^j X_{i(t-j)} + \varepsilon_{it} \tag{15}$$

In this framework, δ_i^j and η_i^j represent the autoregressive coefficients and elasticity, respectively, with both assumed to exhibit variation across distinct cross-sectional units. The null and alternative hypotheses are defined as follows (16, 17):

$$h_0: \mu_i = 0 \quad \text{for } \forall \text{I} \tag{16}$$

$$h_1: (\mu_i = 0 \; for \; all \; i = 1,2,3,4, \dots, N_1 \; \mu_i \neq 0 \; for \; all \; i = N_1 + 1,2,3,4, \dots, N) \tag{17}$$

The hypotheses are tested using Wald statistics, which are computed as outlined in equation (18).

$$W_{N,T}^{HNC} = N^{-1} \sum_{i=1}^{N} W_{i,T} \tag{18}$$

Here, $W_{i,T}$ signifies the Wald test statistic, which is calculated for each individual unit *i*.

3. Empirical Findings

Table 2 summarizes the descriptive statistics for twelve variables. Mean values show central patterns, with average exports at 1367444063 and a digitalization score of 0.049. Standard deviations reveal substantial dispersion in exports, GDP measures, partner-country exchange rates, digital distance, and economic complexity. Jarque–Bera results confirm non-normal distributions ($p<0.05$), underscoring the need for robust or non-parametric analytical techniques.

Table 2
Preliminary statistics

Variables	Mean	Std. Deviation	Maximum	Minimum	Prob.
$Export_{tr}$	1367444063	2556329671	21141783053	154635	0.000
GDP_{tr}	854043829491	188716078094	1194401442556	566434966772	0.000
GDP_{k}	649573589601	2153876852198	21443388432051	99130304	0.000
$Exchange_{tr}$	4.281	3.939	16.549	1.302	0.000
$Exchange_{k}$	2316.219	23732.128	386444	0.214	0.000
$DigiD$	0.049	0.256	0.54	-0.51	0.000
$DigiD_{ict}$	0.017	0.255	0.56	-0.62	0.000
$DigiD_{skills}$	0.022	0.234	0.55	-0.54	0.000
$DigiD_{rd}$	0.168	0.241	0.57	-0.62	0.000
$DigiD_{ia}$	-0.002	0.187	0.58	-0.48	0.000
$DigiD_{af}$	0.044	0.161	0.63	-0.29	0.000
$EciD$	0.379	0.958	2.899	-1.927	0.000

Table 3 reports correlations between economic variables and digital distance, showing mixed directional links. Turkey's exports and partner-country GDP display weak to moderate negative associations with digital distance, while Turkey's GDP and both exchange-rate measures exhibit positive correlations, suggesting these indicators rise as digital disparities between Turkey and its partners increase.

Table 3
Correlation matrix

Variables	$Export_{tr}$	GDP_{tr}	GDP_k	$Exchange_{tr}$	$Exchange_k$	$DigiD$	$DigiD_{ict}$	$DigiD_{skills}$	$DigiD_{rd}$	$DigiD_{ia}$	$DigiD_{af}$	$EciD$
$Export_{tr}$	1											
GDP_{tr}	0.119	1										
GDP_k	0.415	0.035	1									
$Exchange_{tr}$	0.115	0.835	0.029	1								
$Exchange_k$	-0.034	0.028	-0.023	-0.003	1							
$DigiD$	-0.393	0.087	-0.351	0.059	0.102	1						
$DigiD_{ict}$	-0.322	-0.112	-0.185	-0.034	0.072	0.861	1					
$DigiD_{skills}$	-0.326	0.193	-0.186	0.125	0.115	0.902	0.749	1				
$DigiD_{rd}$	-0.512	0.082	-0.551	0.071	0.069	0.872	0.654	0.699	1			
$DigiD_{ia}$	-0.227	0.022	-0.294	-0.006	0.079	0.799	0.623	0.603	0.681	1		
$DigiD_{af}$	-0.181	0.256	-0.305	0.169	0.096	0.765	0.589	0.653	0.641	0.601	1	
$EciD$	-0.359	0.086	-0.322	0.079	0.069	0.898	0.777	0.779	0.793	0.812	0.672	1

Selecting a suitable estimator is essential for managing cross-sectional dependence and slope heterogeneity in panel datasets, particularly given the interconnected nature of global markets. To evaluate these issues, the Breusch–Pagan LM (Breusch & Pagan, 1980), Pesaran scaled LM, and Pesaran CD tests (Pesaran, 2004) were applied, all indicating significant dependence across countries. Swamy's (1970) and Pesaran–Yamagata's homogeneity tests (2008) further reveal notable slope differences, demonstrating that country-specific dynamics are present and must be incorporated through methods accommodating structural heterogeneity.

Table 4
Cross-sectional dependence and homogeneity tests

Variables	CD_{BP}	CD_{LM}	CD	$\tilde{\Delta}$	$\tilde{\Delta}_{adj}$
Model (1)	15582.561***	91.206***	23.023***	14.147***	19.372***
Model (2)	14521.675***	81.337***	48.664***	14.146***	19.37***
Model (3)	16111.104***	96.123***	23.006***	14.083***	19.284***
Model (4)	15835.426***	93.559***	26.931***	13.917***	19.057***
Model (5)	16877.234***	103.249***	33.819***	14.849***	20.333***
Model (6)	16805.562***	102.583***	34.338***	14.358***	19.661***
Model (7)	17226.587***	106.499***	34.239***	14.528***	19.893***

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

Table 5 reports first-generation unit root results from Im et al. (2003) and Levin et al. (2002), along with second-generation tests by Pesaran (2007). These procedures assess stationarity while accounting for cross-sectional features. All variables are found to be level-stationary, supporting the suitability of panel threshold estimation for subsequent empirical analysis.

Table 5
First- and Second-generation unit root test results

Variables	First-Generation Unit Root Test Results				Second-Generation Unit Root Test Results	
	Im, Pesaran, and Shin		Levin, Lin and Chu		PESCADF	
	Intercept	Intercept and Trend	Intercept	Intercept and Trend	Intercept	Intercept and Trend
$Export_{tr}$	-5.342***	-10.438***	-3.635***	-11.474***	-2.226***	-2.871***
GDP_{tr}	1.861**	-9.979***	17.071***	-12.353***	-2.612***	-2.853***
GDP_{k}	-2.691***	-7.324***	-5.172***	-5.893***	-1.925***	-3.019***
$Exchange_{tr}$	-4.521***	-8.242***	-2.729***	-4.185***	-2.235***	-2.692***
$Exchange_{k}$	-3.839***	-8.423***	-2.953***	-14.033***	-2.281***	-2.457**
$DigiD$	-4.086***	12.962***	-8.571***	-6.714***	-2.293***	-3.085***
$DigiD_{ict}$	-5.405***	-9.464***	-9.051***	-10.267***	-1.878**	-2.593***
$DigiD_{skills}$	-3.619***	-6.478***	-18.881***	-2.741***	-2.671***	-2.483**
$DigiD_{rd}$	-2.966***	-13.683***	-3.458***	-22.184***	-1.991***	-2.648***
$DigiD_{ia}$	-5.508***	-11.309***	-8.735***	-9.638***	-2.156***	-2.887***
$DigiD_{af}$	-3.899***	-7.917***	-16.005***	-8.895***	-2.108***	-2.507***
$EciD$	-3.008***	-4.196***	-3.326***	-12.888***	-1.876**	-2.529***

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

Before estimating the panel threshold regression, the study first identified the appropriate number of thresholds. Using Hansen's (1999) panel threshold framework and a bootstrap procedure repeated 300 times, threshold values were estimated with digital distance serving as the threshold variable (Models 1–6). The results indicate a statistically significant single-threshold structure linking Turkey's exports with the GDP and exchange rates of Turkey and its trading partners, a pattern also confirmed in the robustness specification (Model 7). As shown in Table 5, all single-threshold models are significant at the 1% or 5% levels, verifying the presence of threshold behavior. The estimated threshold values—30.56, 17.16, 88.25, 39.41, 36.57, 38.71, and 39.83—demonstrate that digital distance generates asymmetric effects on export performance depending on its position relative to the threshold, as summarized in Table 6.

Table 6
Threshold existence tests

Variables	Threshold		F Stat.	Prob.	Critical Values		
					%10	%5	%1
Model (1)	Single	0.23	30.56**	0.026	21.503	23.923	33.339
	Double	0.36	13.22	0.331	21.757	26.361	34.603
Model (2)	Single	0.35	17.16**	0.031	14.602	16.852	22.629
	Double	0.31	7.65	0.422	13.692	18.148	22.501
Model (3)	Single	0.15	88.25***	0.000	25.878	30.631	46.067
	Double	0.21	23.81	0.113	25.311	30.281	34.493
Model (4)	Single	-0.07	39.41***	0.010	20.938	26.951	38.298
	Double	0.46	20.82	0.125	21.133	26.683	30.224
Model (5)	Single	0.27	36.57**	0.020	23.681	29.518	37.856
	Double	0.15	11.47	0.164	19.863	21.491	27.089
Model (6)	Single	-0.09	38.71***	0.003	24.051	32.507	38.292
	Double	-0.15	18.74	0.153	27.821	38.079	48.176
Model (7)	Single	0.69	39.83***	0.010	27.042	30.881	39.283
	Double	1.42	14.85	0.487	30.068	33.235	50.905

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

The likelihood ratio function graphs in Figure 3 depict the process of identifying threshold values and constructing confidence intervals. The red dotted lines indicate the approximate 95% confidence level. Overall, the findings confirm the existence of a nonlinear threshold effect when digital distance serves as the threshold variable for the GDP and exchange rates of Turkey and its trading partners (See Figure 3).

To facilitate a comparative analysis within the panel threshold model, this study examines the impact of Turkey and its trading partners' GDP and exchange rates on Turkey's exports, considering the digital distance threshold. Table 7 presents the estimation results of the panel threshold regression. The findings reveal significant threshold effects of GDP and exchange rates on Turkey's exports, which vary across different levels of digital distance. The detailed results are as follows.

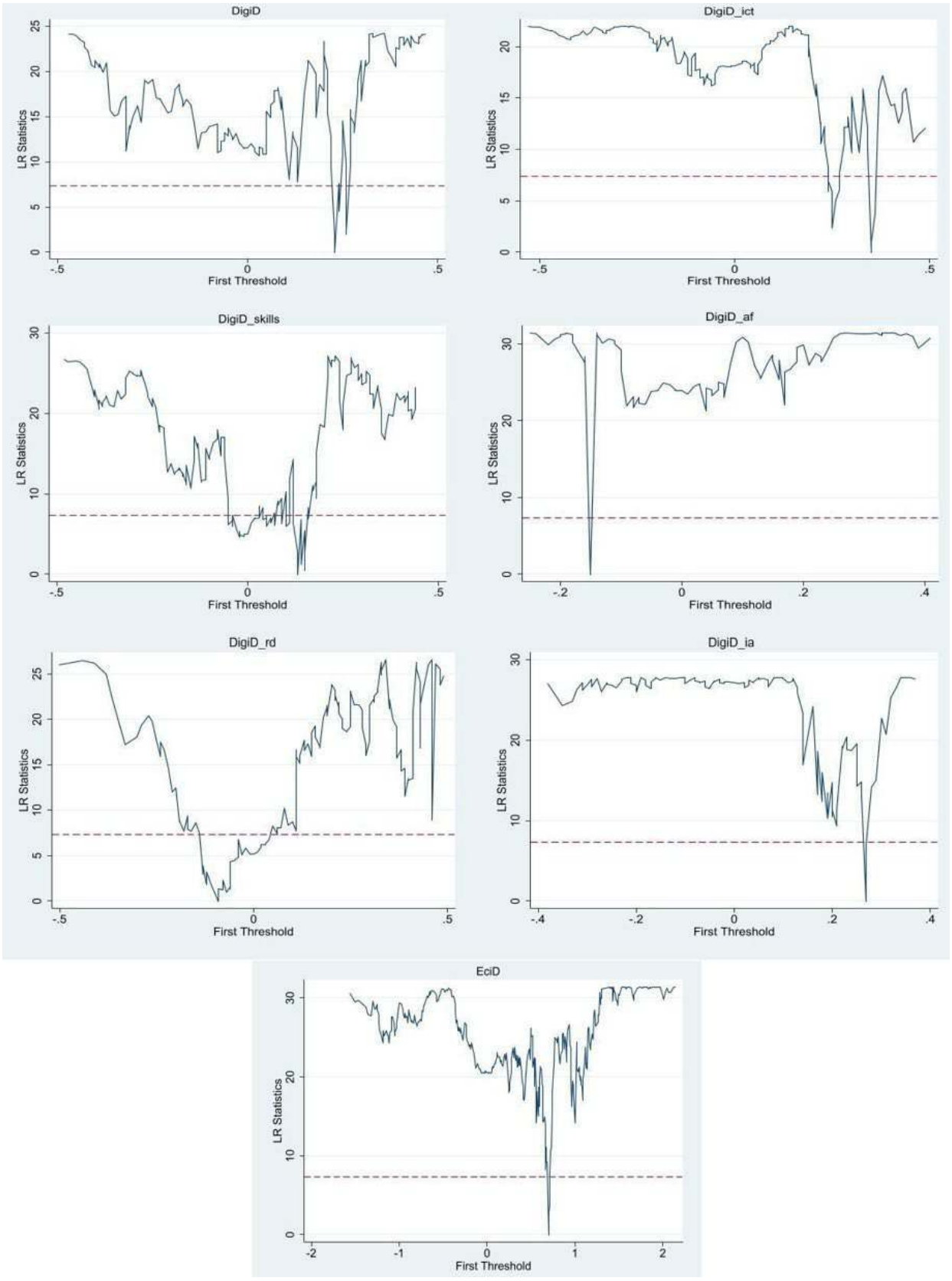

Figure 3. The Likelihood Ratio function graph of modes

Table 7
Estimation results of Threshold models

	Variables	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
Control Variables	GDP_{tr}	1.329***	1.323***	1.263***	1.373***	1.247***	1.651***
	GDP_k	0.221***	0.229***	0.165***	0.224***	0.252***	0.219***
	$Exchange_{tr}$	0.069**	0.058	0.081**	0.065*	0.069**	0.015
	$Exchange_k$	-0.105***	-0.091***	-0.104***	-0.118***	-0.095***	-0.115***
	Constant	-22.364***	-22.372***	-19.248***	-23.744***	-20.829***	-31.034***
Threshold Variables	$DigiD$	-0.808*** (π<0.23)	-	-	-	-	-
		0.316 (0.23<π)	-	-	-	-	-
	$DigiD_{ict}$	-	0.112 (π<0.35)	-	-	-	-
		-	-0.277*** (0.35<π)	-	-	-	-
	$DigiD_{skills}$	-	-	-0.676** (π<0.15)	-	-	-
		-	-	1.642*** (0.15<π)	-	-	-
	$DigiD_{rd}$	-	-	-	-1.483*** (π<-0.07)	-	-
		-	-	-	0.852*** (-0.07<π)	-	-
	$DigiD_{ia}$	-	-	-	-	0.898*** (π<0.27)	-
		-	-	-	-	0.223 (0.27<π)	-
	$DigiD_{af}$	-	-	-	-	-	-1.917*** (π<-0.09)
		-	-	-	-	-	-0.454* (-0.09<π)
	R^2	0.49	0.48	0.51	0.49	0.48	0.49
	F-test	201.26***	198.77***	205.36***	184.75***	202.23***	211.36***
	Observations	1620	1620	1620	1620	1620	1620

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

In Model 1, a single cutoff value separates digital distance into two intervals. When $DigiD$ is below 0.23, the coefficient of –0.808 is significant at the 1% level, indicating a strong positive association: decreases in digital distance correspond to reduced Turkish exports. Above the 0.23 threshold, the link becomes statistically insignificant, suggesting that digital distance

influences Turkey's export performance only up to this cutoff, beyond which the effect diminishes.

In Models 2 through 6, the threshold indicators are linked to the sub-components of digital distance—ICT deployment, Skills, R&D activity, Industry activity, and Access to finance. Each specification identifies a single statistically valid cutoff point. The estimated thresholds—0.35, 0.15, –0.07, 0.27, and –0.09 for Models 2 to 6—are significant at either the 1% or 5% levels. In Model 2, ICT deployment ($DigiD_{ict}$) shows no meaningful effect on exports when its value is below 0.35; once this level is exceeded, the coefficient becomes –0.277 and is highly significant, indicating that a widening ICT gap reduces Turkey's export flows. Model 3 demonstrates that when Skills ($DigiD_{skills}$) falls below 0.15, the coefficient is –0.676 and significant at the 5% level. Beyond the threshold, however, the coefficient rises to 1.642 with strong significance, showing that larger disparities in Skills are associated with higher exports. Model 4 yields a similar pattern: when R&D activity ($DigiD_{rd}$) is below –0.07, the coefficient is –1.483, but it switches to 0.852 above the threshold. These outcomes imply that greater distance in Skills and R&D may support Turkey's export performance. In Model 5, lower Industry activity distance ($DigiD_{ia}$) below 0.27 increases exports, while no significant relationship appears above this level. Finally, Model 6 indicates that greater distance in Access to finance ($DigiD_{af}$) consistently depresses exports, though the adverse effect diminishes once the threshold is crossed.

Table 8
Robustness of threshold model

Variables		Model (7)
Control Variables	GDP_{tr}	1.324***
	GDP_{k}	0. 202***
	$Exchange_{tr}$	0.062*
	$Exchange_{k}$	-0.103***
	Constant	- 21.791***
Threshold Variables	$EciD$	-0.293*** (π<0.69)
		0.168 (0.69<π)
	R^2	0.49
	F-test	206.01***
	Observations	1620

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

Table 8 provides a robustness assessment using a panel threshold model that incorporates the robustness variable. The estimated cutoff for the economic complexity index distance ($EciD$) is 0.69. Below this level, the coefficient is –0.293 and highly significant, while no significant effect appears above it. This implies that narrowing the economic complexity gap reduces Turkey's exports. The pattern mirrors the influence of digital distance, supporting the core model's conclusions.

Table 9
Dumitrescu & Hurlin panel causality test results

Null Hypothesis (h_0)	$Z^{HNC}_{N,T}$	Z^{HNC}_{N}	**Direction of Causality**
$Export_{tr}$ does not Granger-cause GDP_{tr}	4.526***	8.245***	Bi-directional
GDP_{tr} does not Granger-cause $Export_{tr}$	33.282***	50.253***	
$Export_{tr}$ does not Granger-cause GDP_{k}	2.284***	4.971***	Bi-directional
GDP_{k} does not Granger-cause $Export_{tr}$	14.728***	23.148***	
$Export_{tr}$ does not Granger-cause $Exchange_{tr}$	4.762***	8.591***	Bi-directional
$Exchange_{tr}$ does not Granger-cause $Export_{tr}$	32.108***	48.537***	
$Export_{tr}$ does not Granger-cause $Exchange_{k}$	0.875	0.932	Neutrality
$Exchange_{k}$ does not Granger-cause $Export_{tr}$	0.282	0.621	
$Export_{tr}$ does not Granger-cause $DigiD$	0.793	2.792***	Bi-directional
$DigiD$ does not Granger-cause $Export_{tr}$	2.511***	5.301***	
$Export_{tr}$ does not Granger-cause $DigiD_{ict}$	6.844***	11.632***	Bi-directional
$DigiD_{ict}$ does not Granger-cause $Export_{tr}$	1.316	3.556***	
$Export_{tr}$ does not Granger-cause $DigiD_{skills}$	2.234**	4.897***	Bi-directional
$DigiD_{skills}$ does not Granger-cause $Export_{tr}$	10.978***	17.671***	
$Export_{tr}$ does not Granger-cause $DigiD_{rd}$	12.941***	20.537***	Bi-directional
$DigiD_{rd}$ does not Granger-cause $Export_{tr}$	2.711***	5.594***	
$Export_{tr}$ does not Granger-cause $DigiD_{ia}$	5.288***	13.436***	Bi-directional
$DigiD_{ia}$ does not Granger-cause $Export_{tr}$	2.317***	7.833***	
$Export_{tr}$ does not Granger-cause $DigiD_{af}$	3.273***	6.414***	Bi-directional
$DigiD_{af}$ does not Granger-cause $Export_{tr}$	10.425***	16.863***	
$Export_{tr}$ does not Granger-cause $EciD$	5.277***	9.342***	Bi-directional
$EciD$ does not Granger-cause $Export_{tr}$	6.729***	11.462***	

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively.

Table 9 reports the outcomes of the Dumitrescu–Hurlin heterogeneous panel causality test, highlighting notable causal interactions among the

examined variables. The results show robust two-way causality between Turkey's export performance and nearly all variables, except the partner country's exchange rate. ICT investment, a key dimension of digitalization, exhibits reciprocal causality with exports, aligning with Goldar (2023). Likewise, R&D investment demonstrates mutual causality with exports, supporting evidence from Gocer (2013) and Altiner et al. (2022). A similar bidirectional link emerges between access to finance and exports, consistent with Tran et al. (2024). Overall, the findings underscore how economic and digital progress both shape and respond to Turkey's export activity.

4. Conclusion and Policy Recommendations

Extensive research has explored how distance shapes international trade. As technology accelerates digitalization, differences in countries' digital capacities have introduced a new form of separation: digital distance. This shift makes examining its influence on trade increasingly important. Traditional trade models emphasize geographic and cultural barriers but largely ignore digital gaps, despite substantial evidence on the trade effects of technological progress. Incorporating digital distance can therefore fill a notable void in existing trade theory.

The empirical findings of this study demonstrate that digital distance has become a critical determinant of Turkey's export performance, transcending the traditional notions of geographical and cultural distance emphasized in the gravity model of international trade (Huang, 2007; Obstfeld & Rogoff, 2000; Rangan & Lawrence, 1999). While geographical distance remains relevant, our analysis reveals that digital disparities—measured through ICT infrastructure, skills, R&D capacity, industrial application, and access to finance—play a far more complex role in shaping bilateral trade dynamics. This aligns with recent research emphasizing that technological differences significantly influence trade flows between countries (Posner, 1961; Soete, 1981; Esfahani & Tayebi, 2016).

An important insight from the analysis is that narrowing digital distance does not consistently enhance Turkey's export performance. Convergence in ICT infrastructure and R&D capabilities tends to weaken exports, while larger gaps in digital skills and R&D unexpectedly stimulate them. This pattern supports Dung's (2024) view that technological distance can have nonlinear effects, and aligns with Cao and Hsu (2025), who show that digitalization

reshapes trade dynamics. Overall, digital distance creates asymmetrical, dimension-specific impacts.

Policy implications suggest Turkey should not pursue uniform digital convergence. Aligning with technological gap theory (Posner, 1961; Soete, 1981), maintaining selective digital advantages through frontier R&D and skill development can sustain temporary export benefits, rather than eliminating all digital disparities with trading partners.

Second, the finding that gaps in ICT capacity and financial access hinder exports highlights the need for stronger digital infrastructure and inclusive financing (Goldar, 2023; Manickam et al., 2021). Strengthening digital finance tools, supporting venture capital for tech-driven firms, and promoting international ICT partnerships would help Turkey improve export performance (Tran et al., 2024).

Third, the asymmetric role of digital skills and R&D capacity suggests that human capital formation and innovation ecosystems must remain central to Turkey's trade strategy. As demonstrated by Altiner et al. (2022) and Gocer (2013), R&D expenditures directly boost high-tech exports, while Lopez et al. (2022) and Hong and Nam (2021) emphasize that firm-level innovations strengthen international competitiveness. Accordingly, Turkey should reinforce digital education, incentivize private-sector R&D investment, and create innovation clusters to sustain export dynamism.

Fourth, the findings highlight the need to embed digital distance considerations into Turkey's broader trade policy and negotiation strategies. As Abendin et al. (2022) show for West Africa, digitalization significantly enhances bilateral trade, while Wang et al. (2024) caution that excessive digital distance can hinder cross-border M&As. Turkey must therefore negotiate digital trade agreements that reduce excessive asymmetries while safeguarding its comparative advantages in selected technologies.

Finally, given the nonlinear and threshold effects observed, trade policy must become more adaptive. Policymakers should employ continuous monitoring of digital distance indicators such as UNCTAD's Frontier Technological Readiness Index and Harvard's Economic Complexity Index to design dynamic interventions. This echoes the growing literature advocating for data-driven, adaptive policy frameworks in an era of technological disruption (Ajide et al., 2025; Ji et al., 2022).

In conclusion, the threshold-based analyses presented here offer a basis for future research to implement econometric approaches that mitigate endogeneity concerns, particularly by incorporating lagged values of the dependent variable through dynamic panel estimators such as the system

generalized method of moments (system-GMM) and comparable methodologies.

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