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Artificial Intelligence, Digitalization, and Economic Performance: Does Cybersecurity Regulation Matter?

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Abstract

This study investigates the effects of artificial intelligence (AI), digitalization, and cybersecurity regulation on economic performance in Pakistan, with a focus on the moderating role of cybersecurity regulation. Using annual data from 2000 to 2025 and an autoregressive distributed lag (ARDL) framework, the study evaluates both direct and conditional effects of technological transformation. The results reveal that AI and digitalization positively affect economic performance, while foreign direct investment, gross fixed capital formation, and trade openness also contribute positively. Cybersecurity regulation exhibits a negative direct effect, indicating potential short-term compliance and adjustment costs. However, the interaction results demonstrate that cybersecurity regulation significantly strengthens the positive effects of both AI and digitalization on economic performance. These findings highlight cybersecurity regulation as a complementary institutional mechanism for technological development. The study recommends integrating AI development, digitalization, and proportionate cybersecurity governance to strengthen digital trust, reduce technological risks, and maximize the economic benefits of Pakistan's digital transformation.

Keywords: Artificial Intelligence (AI); Digitalization; Cybersecurity; Interaction Terms; ARDL.

Introduction

Artificial intelligence (AI) and digitalization are increasingly reshaping the foundations of modern economic activity by transforming production systems, business models, public administration, financial services, and market organization. Advances in AI allow firms and public institutions to automate routine processes, improve forecasting and decision-making, optimize resource allocation, and develop new products and services. Digitalization complements these developments by expanding connectivity, reducing information and transaction costs, facilitating electronic commerce, and improving access to markets and financial services. These technological transformations have therefore become increasingly relevant to productivity, competitiveness, innovation, and long-term economic performance. For developing economies in particular, AI and digital technologies offer opportunities to overcome conventional constraints on growth and

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accelerate structural transformation. Nevertheless, realizing these economic benefits requires more than technological adoption because the expansion of digitally interconnected economic activities also generates new institutional and regulatory challenges.

One of the most significant challenges associated with accelerated digital transformation is the increasing exposure of households, firms, financial institutions, and governments to cybersecurity risks. Greater reliance on digital platforms, cloud infrastructure, electronic payments, data-intensive technologies, and AI-enabled systems expands the potential surface for cyberattacks, data breaches, fraud, disruption of critical infrastructure, and unauthorized access to information. These risks can lead to direct financial losses while also weakening consumer confidence, increasing firms' security and compliance costs, discouraging digital transactions, and creating uncertainty about investment and innovation. Cybersecurity consequently has an economic dimension that extends beyond its conventional treatment as a technical or national-security concern. The economic returns from AI and digitalization may depend in part on whether institutions can establish sufficient security, accountability, and confidence in the digital environment.

Cybersecurity regulation provides an important connection between technological transformation and institutional governance. From a law-and-economics perspective, an effective regulatory framework can reduce information asymmetries, establish responsibilities for protecting digital assets and data, create mechanisms for responding to cyber incidents, and provide greater legal certainty to participants in digital markets. Appropriate regulation may therefore reduce the economic costs of cyber risks and strengthen trust in digital transactions. Conversely, weak enforcement, fragmented institutional responsibilities, or regulatory uncertainty can limit these benefits, while excessively burdensome regulation may increase compliance costs and constrain technological innovation. The relationship between regulation and economic performance is consequently not necessarily automatic. Rather, the effectiveness of cybersecurity regulation may determine the extent to which technological advancement is converted into sustainable economic gains.

This relationship is particularly relevant to Pakistan, where digital transformation has become an increasingly important component of the national development agenda. The expansion of internet connectivity, digital financial services, e-commerce, information technology services, digital government, and technology-based entrepreneurship has increased the economic importance of the country's digital ecosystem. More recently, Pakistan has strengthened the institutional basis of this transition through the Digital Nation Pakistan Act 2025 and the National Artificial Intelligence Policy 2025. The latter seeks to establish an ecosystem for responsible AI adoption and explicitly connects technological development with socioeconomic progress and the transition toward a knowledge-based economy. At the same time, the National Cyber Security Policy 2021 provides a governance framework for cybersecurity. It emphasizes institutional coordination, protection of critical information infrastructure, compliance mechanisms, incident response, and legal measures. These developments demonstrate that technological advancement and cybersecurity governance are increasingly interconnected components of Pakistan's economic transformation.

Despite these initiatives, an important question remains: whether technological advancement can translate into stronger economic performance when the supporting cybersecurity regulatory environment is still evolving. Pakistan continues to face structural constraints on sustained economic growth. At the same time, gaps in digital infrastructure, regulatory capacity, institutional coordination, and the enabling environment can limit the economic benefits of digital transformation. The World Bank has emphasized that improving Pakistan's digital infrastructure must be accompanied by regulatory and institutional reforms. At the same time, the Asian Development Bank similarly identifies cybersecurity and policy and regulatory frameworks as important dimensions of Pakistan's digital ecosystem. This issue is significant because expanding AI and digital technologies without corresponding improvements in cybersecurity governance may increase technological exposure without generating proportional economic gains. Examining cybersecurity regulation alongside AI and digitalization can therefore provide a more comprehensive explanation of the institutional conditions under which technological transformation contributes to Pakistan's economic development.

Against this background, this study aims to investigate the effects of artificial intelligence and digitalization on economic performance in Pakistan and, more importantly, to determine whether cybersecurity regulation influences these relationships. Specifically, the study examines the direct effects of AI, digitalization, and cybersecurity regulation on economic performance and evaluates whether cybersecurity regulation moderates the economic effects of AI and digitalization. By integrating technological development with the legal and regulatory environment, the study seeks to bridge the conventional separation between digital-economy research and cybersecurity governance. The study contributes to the emerging law-and-economics literature by treating cybersecurity regulation not merely as a legal response to technological risks but as an institutional mechanism that can shape the economic returns of digital transformation. The findings are expected to provide evidence relevant to Pakistan's evolving AI, digitalization, and cybersecurity frameworks and to inform the design of regulatory policies that simultaneously encourage technological innovation, strengthen digital security, and support sustainable economic performance.

Literature Review and Hypothesis Development

Artificial Intelligence and Economic Performance

Artificial intelligence has emerged as an important component of technological change because of its capacity to automate tasks, process large volumes of information, improve prediction, and complement human decision-making. From the perspective of endogenous growth theory, technological innovation can support long-run economic growth by improving productivity, generating knowledge spillovers, and increasing the efficiency with which capital and labor are utilized (Romer, 1990; Aghion and Howitt, 1992). AI extends these mechanisms by introducing technologies capable of performing cognitive and analytical tasks that humans traditionally performed. Consequently, AI is increasingly regarded as a general-purpose technology whose economic effects can diffuse across industries rather than remaining concentrated within the information technology sector (Cockburn et al., 2019; Agrawal et al., 2019).

The economic implications of AI have been examined through the channels of productivity, employment, innovation, and growth. Brynjolfsson et al. (2017) argue that the productivity benefits of transformative technologies may not appear immediately because firms require complementary investments in organizational restructuring, human capital, and intangible assets before technological capabilities translate into measurable productivity gains. This argument is particularly relevant to AI, where technological availability does not necessarily imply effective economic adoption. Aghion et al. (2019) similarly suggest that AI has considerable potential to affect economic growth through automation and innovation. However, its aggregate effects depend on the rate of technological diffusion and the capacity of economies to adapt production structures.

More recent evidence reinforces the potential productivity effects of AI while emphasizing substantial uncertainty surrounding their magnitude. Filippucci et al. (2024) identify several mechanisms by which AI can improve productivity, including task automation, worker augmentation, innovation, and organizational efficiency. Their analysis nevertheless emphasizes that aggregate gains depend considerably on adoption rates, sectoral exposure, complementary investments, and institutional conditions. Similarly, Comunale and Manera (2024), in their review of the economic literature on AI, conclude that theoretical studies generally predict significant implications for productivity and economic growth. In contrast, empirical evidence remains less conclusive because widespread AI adoption is comparatively recent. Estimates of macroeconomic productivity gains also vary with assumptions about AI diffusion and the extent to which task-level productivity improvements translate into economy-wide efficiency gains (Filippucci et al., 2024).

These considerations are particularly important for developing economies. AI can help emerging economies improve public service delivery, financial inclusion, agricultural productivity, industrial efficiency, and knowledge-intensive services. However, inadequate digital infrastructure, shortages of specialized human capital, financing constraints, and weak institutional frameworks can prevent economies from fully capturing these benefits. Recent assessments indicate that lower- and middle-income economies may therefore experience substantially different productivity outcomes from AI compared with technologically advanced economies (Chaar et al., 2025). Pakistan exhibits several of these structural characteristics, making the relationship between AI development and economic performance an empirical rather than predetermined question. Nevertheless, improvements in AI readiness and adoption are expected to strengthen productive efficiency and technological capabilities when complementary conditions are available. Accordingly, the following hypothesis is proposed:

H1: Artificial intelligence positively affects economic performance in Pakistan.

Digitalization and Economic Performance

Digitalization represents a broader transformation through which digital technologies become integrated into economic transactions, production systems, communication networks, financial activities, and public administration. Unlike AI, which represents a particular technological capability, digitalization captures the infrastructure and adoption processes that allow information to be generated, transmitted, and utilized electronically across the economy. The expansion of internet access, mobile connectivity, digital financial services, broadband infrastructure, electronic commerce, and digital public services can reduce information asymmetries and transaction costs while increasing market accessibility and organizational efficiency (Goldfarb and Tucker, 2019).

A substantial body of empirical literature associates information and communication technologies with productivity and economic growth. Roller and Waverman (2001) find evidence that telecommunications infrastructure contributes positively to economic development by generating network externalities. Czernich et al. (2011) similarly demonstrate that broadband infrastructure

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can contribute to economic growth by increasing information flows and facilitating new forms of commercial activity. Vu (2011) finds that information and communication technology is an important source of economic growth, although the magnitude of the effect varies with countries' absorptive capacities. These findings suggest that digital infrastructure functions not only as a communications technology but also as productive capital that facilitates wider economic interactions.

Digitalization can influence economic performance through several interconnected mechanisms. Digital platforms reduce search and transaction costs, improve communication between firms and consumers, facilitate access to larger markets, and enable firms to reorganize production and supply chain activities. Digital financial technologies can also reduce barriers to accessing financial services, while digital government can lower administrative costs and improve the efficiency of public service delivery. Myovella et al. (2020) show that digitalization contributes to economic growth in both developed and developing economies, although differences in infrastructure and institutional capacity affect the size of these benefits. Similarly, Habibi and Zabardast (2020) identify positive economic effects associated with information and communication technologies, while emphasizing the importance of complementary human capital conditions.

The digital economy is especially relevant for Pakistan because the country's large population, expanding connectivity, growing information-technology services sector, digital payment systems, and e-commerce activities provide substantial scope for technology-enabled economic expansion. At the same time, the economic gains from digitalization may remain constrained when access, infrastructure quality, digital literacy, regulatory effectiveness, and institutional capabilities are uneven. This implies that simply increasing connectivity may not be sufficient; the productivity effects of digitalization depend on the extent to which digital infrastructure becomes integrated into productive economic activities. Nevertheless, the reduction in transaction costs, expansion of information flows, and improvement in market accessibility associated with digitalization provide a theoretical basis for expecting a positive economic effect. Therefore:

H2: Digitalization positively affects economic performance in Pakistan.

Cybersecurity Regulation and Economic Performance

The increasing dependence of economic activity on digital technologies has simultaneously increased exposure to cybercrime, data breaches, service disruptions, financial fraud, intellectual-property theft, and attacks on critical information infrastructure. Cybersecurity, therefore, generates economic consequences that extend beyond technical information-security considerations. Anderson et al. (2013) demonstrate that cybercrime produces substantial direct and indirect economic costs, while Gordon et al. (2015) show that cybersecurity risks can affect corporate decision-making and investment in information security. Cyber incidents can also cause reputational losses, disrupt business operations, erode consumer confidence, and heighten uncertainty around digital transactions.

Law and economics provide an important framework for understanding the role of cybersecurity regulation in addressing these problems. Digital markets can suffer from information asymmetries and negative externalities because organizations may not bear the full social costs generated by inadequate cybersecurity practices. Firms consequently may underinvest in cybersecurity when some of the costs of breaches are transferred to customers, interconnected businesses, or wider digital networks. Regulatory intervention can address this market failure by establishing minimum security requirements, reporting obligations, liability rules, data protection responsibilities, and enforcement mechanisms. Such rules can improve incentives for cybersecurity investment and reduce uncertainty about participants' responsibilities in digital markets.

However, the economic effects of cybersecurity regulation are theoretically ambiguous. Well-designed regulation can increase confidence in digital systems, protect information assets, reduce expected losses from cyber incidents, and facilitate investment in digitally intensive activities. Conversely, regulatory requirements can generate compliance expenditures and impose additional costs on firms, particularly when regulatory standards are complex or institutional enforcement is uncertain. Recent empirical evidence illustrates this trade-off. Jin et al. (2025), examining China's Cybersecurity Law as a quasi-natural experiment, find that cybersecurity regulation significantly promotes corporate digital transformation, suggesting that legal requirements can encourage firms to strengthen their digital capabilities. In contrast, Jin et al. (2025) report that cybersecurity law can reduce corporate investment by increasing financing constraints and perceived corporate risks. These contrasting findings demonstrate why the economic implications of cybersecurity regulation cannot be assumed to be uniformly positive.

This issue is particularly relevant to Pakistan, where cybersecurity governance is developing alongside rapid expansion in digital economic activities. Bokhari (2023) identifies several institutional and implementation factors that affect the effectiveness of cybersecurity laws and regulations in Pakistan, indicating that the mere existence of legislation does not ensure effective regulatory outcomes. The economic significance of cybersecurity regulation consequently depends on enforcement capacity, institutional coordination, legal clarity, and the ability of regulatory arrangements to create confidence without imposing disproportionate compliance burdens. Nevertheless, where regulation successfully reduces cyber risks and improves confidence in digital economic activities, it can create institutional conditions supportive of economic performance. This leads to the following hypothesis:

H3: Cybersecurity regulation positively affects economic performance in Pakistan.

Moderating Role of Cybersecurity Regulation in the AI–Economic Performance Relationship

The economic benefits generated by AI increasingly depend on the collection, processing, storage, and exchange of large quantities of digital information. This dependence makes AI-intensive economic activity particularly sensitive to cybersecurity vulnerabilities. AI systems may expose organizations to data theft, algorithm manipulation, unauthorized access to systems, privacy violations, and disruptions to digitally interconnected operations. Consequently, economies with expanding AI capabilities but inadequate cybersecurity governance may experience greater technological exposure without obtaining equivalent improvements in economic performance.

Institutional theory suggests that effective rules and enforcement mechanisms reduce uncertainty and provide economic actors with predictable conditions for investment and innovation (North, 1990). Applied to AI, cybersecurity regulation can provide legal safeguards governing digital systems, data security, organizational responsibilities, and responses to cyber incidents. Such institutional safeguards may improve business and consumer confidence and encourage organizations to deploy AI technologies in economically productive activities. The productivity effects of

AI may therefore depend partly on whether cybersecurity institutions develop alongside technological capabilities.

The emerging literature on AI regulation supports the importance of this institutional dimension. Comunale and Manera (2024) emphasize that the economic consequences of AI cannot be separated from evolving regulatory concerns relating to privacy, security, competition, and governance. Filippucci et al. (2024) similarly argue that realizing AI-related productivity gains requires appropriate complementary policies and institutional conditions. At the same time, excessively restrictive regulation can slow innovation and increase adoption costs, indicating that regulatory quality rather than regulation alone is important. In Pakistan, where AI governance and cybersecurity institutions are developing simultaneously, cybersecurity regulation may consequently determine whether improvements in AI readiness translate into stronger economic outcomes. Thus:

H4: Cybersecurity regulation positively moderates the relationship between artificial intelligence and economic performance in Pakistan.

Moderating Role of Cybersecurity Regulation in the Digitalization–Economic Performance Relationship

Cybersecurity regulation may also condition the economic effects of broader digitalization. Digital transformation increases interconnectivity among consumers, businesses, financial institutions, and government agencies, generating efficiency gains but simultaneously expanding opportunities for malicious cyber activity. Trust, therefore, represents an important economic asset in digitally mediated transactions. When consumers or firms perceive digital systems as insecure, they may avoid online transactions, limit information exchange, or reduce investment in digital technologies, thereby weakening the economic returns from digital infrastructure.

The relationship can be interpreted through the lens of transaction-cost economics and institutional economics. Digitalization reduces many conventional transaction costs by making communication, information exchange, contracting, and payments faster and less expensive. Cyber insecurity, however, introduces new expected costs associated with fraud, data loss, service disruption, monitoring, and risk management. Appropriate cybersecurity regulation can reduce these costs by establishing standards of conduct, defining organizational responsibilities, improving incident-management arrangements, and strengthening confidence in digital markets. Evidence that cybersecurity regulation can promote firms' digital transformation supports the proposition that regulation may complement rather than constrain digital development (Jin et al., 2025). Recent evidence on digital trust also indicates that cybersecurity and secure digital infrastructure are closely linked to broader socioeconomic outcomes (Qazi and Aziz, 2026).

This moderating mechanism is highly relevant to Pakistan, as the country is simultaneously expanding digital public infrastructure, financial technology, e-commerce, digital government, and digitally delivered services. Weak cybersecurity governance could reduce the returns from these investments if increasing digital dependence is accompanied by rising security risks and declining user confidence. Conversely, effective regulation can provide a more predictable and secure institutional environment within which businesses and households utilize digital technologies. Cybersecurity regulation can therefore function as an enabling institutional mechanism that determines how effectively digitalization translates into economic performance. Accordingly, the final hypothesis is formulated as follows:

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H5: Cybersecurity regulation positively moderates the relationship between digitalization and economic performance in Pakistan.

Research Gap

Despite the growing literature on artificial intelligence, digitalization, and economic performance, several important gaps remain, particularly in developing economies such as Pakistan. Existing studies have largely examined the economic effects of AI and digitalization independently, with considerable emphasis on productivity, innovation, employment, and economic growth. At the same time, cybersecurity has predominantly been approached as a technical, organizational, or national security concern. Consequently, limited attention has been paid to the economic role of the legal and regulatory environment accompanying technological transformation. More importantly, the existing literature provides insufficient evidence on whether cybersecurity regulation conditions the extent to which AI and digitalization translate into improved economic performance. This omission is particularly significant for Pakistan, where the rapid expansion of digital services and the emerging adoption of AI are occurring alongside an evolving cybersecurity governance framework. Although previous Pakistan-focused studies have discussed cybersecurity legislation, institutional capacity, digital transformation, and implementation challenges, the interaction between these regulatory arrangements and the economic returns from AI and digitalization remains underexplored. Thus, an important research gap exists at the intersection of law, technological transformation, and economic performance. Addressing this gap, the present study integrates AI, digitalization, and cybersecurity regulation within a unified empirical framework. It investigates not only their direct effects on Pakistan's economic performance but also whether cybersecurity regulation moderates the economic effects of AI and digitalization.

Theoretical and Conceptual Foundation

The theoretical foundation of this study is primarily grounded in endogenous growth theory and institutional theory, complemented by the law-and-economics perspective. Endogenous growth theory emphasizes that technological progress, knowledge accumulation, innovation, and human capital are internal drivers of sustained economic growth (Romer, 1990; Aghion and Howitt, 1992). Within this framework, artificial intelligence can enhance economic performance by improving decision-making, automating productive activities, facilitating innovation, and increasing the efficiency of capital and labor. Digitalization similarly contributes to economic performance by reducing information and transaction costs, improving connectivity, expanding market access, and facilitating more efficient production and service delivery. However, technological adoption alone may not guarantee economic gains, as the benefits of AI and digitalization depend on complementary institutional conditions and on an economy's capacity to manage the risks associated with technological transformation.

Institutional theory explains the role of cybersecurity regulation in this relationship. Institutions establish formal rules, enforcement mechanisms, and governance structures that influence economic incentives and reduce uncertainty in market interactions (North, 1990). In an increasingly digital economy, cyber threats, data breaches, online fraud, and disruptions to digital infrastructure can increase transaction costs and discourage businesses and consumers from adopting technology. From a law-and-economics perspective, cybersecurity regulation can address these mar-

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ket failures by establishing security responsibilities, legal accountability, compliance requirements, and mechanisms for managing cyber risks. Effective regulation may consequently strengthen digital trust, reduce uncertainty, and create a more secure environment for technology-based economic activities. However, poorly designed or excessively restrictive regulation may increase compliance costs and constrain innovation, suggesting that the economic value of regulation depends on its effectiveness and institutional implementation.

Based on these theoretical arguments, the conceptual framework posits that artificial intelligence, digitalization, and cybersecurity regulation directly influence Pakistan's economic performance. More importantly, cybersecurity regulation is conceptualized as a moderating institutional mechanism that can alter the economic returns generated by AI and digitalization. Stronger cybersecurity governance is expected to reinforce these relationships by reducing digital risks and strengthening confidence in technology-intensive activities. This integrated framework, therefore, connects technological progress with legal and institutional governance and provides a basis for assessing whether Pakistan's economic gains from AI and digital transformation depend on the effectiveness of its cybersecurity regulatory environment.

Data and Methodology

This study examines the effects of artificial intelligence, digitalization, and cybersecurity regulation on economic performance in Pakistan using annual time-series data for 2000–2025. Economic performance (EP) is the dependent variable, while artificial intelligence (AI), digitalization (DIG), and cybersecurity regulation (CYB) are the principal explanatory variables. Foreign direct investment (FDI), gross fixed capital formation (GFCF), and trade openness (TROP) are included as macroeconomic controls. FDI captures foreign capital and technology inflows, GFCF represents investment in productive assets and productive capacity, and TROP captures Pakistan’s integration with international markets. Macroeconomic series are obtained from the World Development Indicators, while AI, digitalization, and cybersecurity-regulation measures are compiled from their respective international sources. Variables may be transformed into natural logarithms where their measurement and distribution make an elasticity interpretation appropriate.

Baseline empirical specification

The baseline model identifies the direct effects of AI, digitalization, and cybersecurity regulation after controlling for the three macroeconomic determinants. No interaction term is included in the baseline specification:

$$EP_t = \beta_0 + \beta_1 AI_t + \beta_2 DIG_t + \beta_3 CYB_t + \beta_4 FDI_t + \beta_5 GFCF_t + \beta_6 TROP_t + \varepsilon_t \quad (1)$$

where t denotes year, β_0 is the intercept, β_1–β_6 are the long-run parameters of interest, and ε_t is the disturbance term. The coefficients β_1, β_2, and β_3 capture the direct relationships of AI, digitalization, and cybersecurity regulation with economic performance, respectively.

Unit-root testing and ARDL bounds framework

Because the analysis uses annual time-series data, the stationarity properties of all variables are examined before long-run estimation. The Augmented Dickey–Fuller (ADF) test is used to determine whether each series is stationary in levels (I(0)) or after first differencing (I(1). The ARDL bounds approach is appropriate when regressors are a mixture of I(0) and I(1), but it is not valid when any variable is I(2). Following Pesaran, Shin, and Smith (2001), the unrestricted error-correction representation of the baseline model is specified as:

$$\Delta EP_t = \alpha_0 + \Sigma_{i=1}^{p} \varphi_i \Delta EP_{t-i} + \Sigma_{j=0}^{q_1} \theta_{1j} \Delta AI_{t-j} + \Sigma_{j=0}^{q_2} \theta_{2j} \Delta DIG_{t-j} + \Sigma_{j=0}^{q_3} \theta_{3j} \Delta CYB_{t-j} + \Sigma_{j=0}^{q_4} \theta_{4j} \Delta FDI_{t-j} + \Sigma_{j=0}^{q_5} \theta_{5j} \Delta GFCF_{t-j} + \Sigma_{j=0}^{q_6} \theta_{6j} \Delta TROP_{t-j} + \lambda_1 EP_{t-1} + \lambda_2 AI_{t-1} + \lambda_3 DIG_{t-1} + \lambda_4 CYB_{t-1} + \lambda_5 FDI_{t-1} + \lambda_6 GFCF_{t-1} + \lambda_7 TROP_{t-1} + u_t \quad (2)$$

The first-difference terms capture short-run dynamics, while the lagged level terms are used to test for a long-run relationship. The bounds-test null hypothesis is H_0: $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0$, against the alternative that at least one level coefficient is non-zero. Cointegration is supported when the calculated F-statistic exceeds the relevant upper-bound critical value; a statistic below the lower bound indicates no level relationship, while a value between the bounds is inconclusive.

Long-run and short-run ARDL models

Once cointegration is established, the long-run relationship is represented as:

$$EP_t = \delta_0 + \delta_1 AI_t + \delta_2 DIG_t + \delta_3 CYB_t + \delta_4 FDI_t + \delta_5 GFCF_t + \delta_6 TROP_t + \nu_t \quad (3)$$

The associated error-correction model is used to estimate short-run adjustments toward the long-run equilibrium:

$$\Delta EP_t = c_0 + \Sigma_{i=1}^{p-1} \rho_i \Delta EP_{t-i} + \Sigma_j \gamma_{1j} \Delta AI_{t-j} + \Sigma_j \gamma_{2j} \Delta DIG_{t-j} + \Sigma_j \gamma_{3j} \Delta CYB_{t-j} + \Sigma_j \gamma_{4j} \Delta FDI_{t-j} + \Sigma_j \gamma_{5j} \Delta GFCF_{t-j} + \Sigma_j \gamma_{6j} \Delta TROP_{t-j} + \psi ECT_{t-1} + e_t \quad (4)$$

$$ECT_{t-1} = EP_{t-1} - (\delta_0 + \delta_1 AI_{t-1} + \delta_2 DIG_{t-1} + \delta_3 CYB_{t-1} + \delta_4 FDI_{t-1} + \delta_5 GFCF_{t-1} + \delta_6 TROP_{t-1}) \quad (5)$$

The coefficient ψ is expected to be negative and statistically significant. Its magnitude measures the speed at which short-run deviations from equilibrium are corrected in the subsequent period.

Moderating role of cybersecurity regulation

A separate specification evaluates whether changes in cybersecurity regulation affect the economic returns to AI and digitalization. Consistent with the research design, the moderation model excludes FDI, GFCF, and trade openness and retains the constituent main effects together with the interaction terms:

$$EP_t = \alpha_0 + \alpha_1 AI_t + \alpha_2 DIG_t + \alpha_3 CYB_t + \alpha_4 (AI_t * CYB_t) + \alpha_5 (DIG_t * CYB_t) + \mu_t \quad (6)$$

Here, α_4 measures whether cybersecurity regulation changes the effect of AI on economic performance, whereas α_5 measures whether it changes the effect of digitalization on economic performance. A positive and statistically significant interaction coefficient indicates a strengthening moderating effect; a negative coefficient indicates that the regulatory environment weakens the corresponding technological effect.

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The conditional marginal effects implied by Equation (6) are:

$$\partial EP_t / \partial AI_t = \alpha_1 + \alpha_4 CYB_t \quad (7)$$

$$\partial EP_t / \partial DIG_t = \alpha_2 + \alpha_5 CYB_t \quad (8)$$

Equations (7) and (8) make the moderation interpretation explicit: the estimated effect of AI or digitalization is conditional on the observed level of cybersecurity regulation.

Table 1: Variables Sign and Description

Symbol	Variable	Role
EP	Economic performance as GDP per capita growth / GDP growth	Dependent variable
AI	Artificial Intelligence Government AI Readiness Index	Independent variable
DIG	Digitalization as Patent Applications	Independent variable
CYB	Cybersecurity regulation as a Legal Measures pillar / regulatory measure	Moderating variable
FDI	Foreign direct investment as FDI, net inflows in % of GDP	Control variable
GFCF	Gross fixed capital formation as % of GDP	Control variable
TROP	Trade openness as (Exports + Imports)/GDP	Control variable
AI*CYB	AI-cybersecurity interaction	Moderating term
DIG*CYB	Digitalization-cybersecurity interaction	Moderating term

Note: Sources are WDI of the World Bank, Oxford Insights, and the ITU Cybersecurity Index

Results and Discussion

Table 2 presents the descriptive characteristics of the variables used to examine the relationship between artificial intelligence, digitalization, cybersecurity regulation, and economic performance in Pakistan. Economic performance, measured by GDP growth, has a mean of 3.992 and a standard deviation of 2.188, indicating considerable fluctuations in Pakistan's economic performance during the study period. GDP growth ranges from −1.300 to 8.000, reflecting periods of both economic contraction and relatively strong expansion. AI records an average value of 32.284, whereas digitalization has a mean of 16.150. The relatively high standard deviation of digitalization (17.356) indicates substantial changes in Pakistan's digital development over the sample period. Cybersecurity similarly exhibits considerable variation, with values ranging from 4.613 to 100 and a standard deviation of 30.370. This variation reflects the progressive development of Pakistan's cybersecurity environment alongside its broader digital transformation. Among the control variables, FDI averages 0.925% of GDP, while GFCF and trade openness record mean values of 13.933% and 28.404%, respectively. Overall, the descriptive statistics demonstrate sufficient temporal variation across the variables to investigate how technological development, cybersecurity, investment, and international economic integration are associated with Pakistan's economic performance.

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Table 2: Descriptive Statistics

Variable	N	Mean	Std. Dev.	Min	25%	Median	75%	Max
EP	26	3.992	2.188	-1.300	3.125	3.850	5.175	8.000
AI	26	32.284	9.186	9.168	28.361	32.331	39.897	45.700
DIG	26	16.150	17.356	0.687	6.575	8.550	16.638	66.832
CYB	26	34.752	30.370	4.613	14.271	16.268	50.592	100.000
FDI	26	0.925	0.730	0.300	0.514	0.700	0.864	3.000
GFCF	26	13.933	1.377	10.720	13.212	13.895	14.590	16.570
TROP	26	28.404	3.545	21.400	25.800	28.100	31.200	34.400

The correlation results provide preliminary evidence regarding the relationships among the study variables. AI is positively associated with digitalization (0.640) and cybersecurity (0.704), indicating that improvements in Pakistan's AI capabilities have occurred alongside broader digital development and improvements in cybersecurity preparedness. The particularly strong positive correlation between digitalization and cybersecurity (0.947) suggests that cybersecurity development has closely accompanied the expansion of digital technologies. Economically, this relationship is plausible because increasing reliance on digital infrastructure, online transactions, digital financial services, and data-intensive technologies creates greater demand for cybersecurity institutions and regulatory mechanisms. Nevertheless, the magnitude of this correlation suggests potential multicollinearity, meaning that the separate effects of digitalization and cybersecurity should be interpreted with caution in the multivariate analysis. FDI is positively correlated with economic performance (0.208), while GFCF shows a somewhat stronger positive association (0.298), consistent with the expectation that domestic and foreign investment can contribute to productive capacity. The relatively modest correlations between most explanatory variables and economic performance also indicate that a subsequent ARDL analysis is necessary to identify their effects after accounting for other determinants.

Table 3: Correlation Matrix

Variable	EP	AI	DIG	CYB	FDI	GFCF	TROP
EP	1.000						
AI	-0.107	1.000					
DIG	-0.226	0.640	1.000				
CYB	-0.261	0.704	0.947	1.000			
FDI	0.208	-0.092	-0.185	-0.247	1.000		
GFCF	0.298	-0.317	-0.687	-0.632	0.603	1.000	
TROP	-0.111	0.319	0.031	-0.018	0.485	0.304	1.000

The ADF unit-root results demonstrate that the variables have mixed orders of integration. Economic performance is non-stationary at the level but becomes stationary after first differencing, indicating an I(1) process. AI is stationary at the level and is therefore classified as I(0). Digitalization is non-stationary at the level, but becomes stationary after first differencing at the 10% significance level. Cybersecurity, FDI, and GFCF similarly become stationary after first differencing, while trade openness demonstrates weak level stationarity at the 10% level and becomes strongly stationary after first differencing. Importantly, none of the variables is integrated of order two, I(2). The combination of I(0) and I(1) variables provides methodological support for ap-

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plying the ARDL framework, which is specifically suitable for examining short- and long-run relationships when variables exhibit different orders of integration below I(2). The results, therefore, establish the statistical precondition for estimating the proposed ARDL relationship between technological development and economic performance in Pakistan.

Table 4: Unit Root Test

Variable	Form	ADF statistic	p-value	Conclusion
EP	Level	-2.3941	0.1434	Non-stationary at 5%
EP	First difference	-3.1802	0.0212	Stationary
ln(AI)	Level	-5.5570	0.0000	Stationary
ln(DIG)	Level	3.4820	1.0000	Non-stationary
ln(DIG)	First difference	-2.6700	0.0794	Stationary at 10%
ln(CYB)	Level	-1.0960	0.7168	Non-stationary
ln(CYB)	First difference	-3.0500	0.0305	Stationary
ln(FDI)	Level	-2.1640	0.2196	Non-stationary
ln(FDI)	First difference	-4.0640	0.0011	Stationary
ln(GFCF)	Level	0.6020	0.9877	Non-stationary
ln(GFCF)	First difference	-3.3810	0.0116	Stationary
ln(TROP)	Level	-2.5830	0.0966	Stationary at 10%
ln(TROP)	First difference	-5.0520	0.0000	Stationary

Table 5 presents the principal ARDL results and provides strong evidence that technological development contributes to Pakistan's economic performance. AI has a positive and statistically significant coefficient ($\beta = 0.864$, $p < 0.01$), demonstrating that improvements in AI are associated with stronger economic performance. Economically, AI can improve productive efficiency by automating routine processes, improving forecasting and resource allocation, reducing information-processing costs, and complementing human decision-making. These mechanisms are consistent with endogenous growth theory, according to which technological progress and knowledge accumulation generate sustained improvements in productivity and economic activity (Romer, 1990; Aghion & Howitt, 1992). The finding is also consistent with Aghion et al. (2019) 's argument that AI can contribute to economic growth through automation and innovation, while Filippucci et al. (2024) identify worker augmentation, task automation, innovation, and organizational efficiency as important channels through which AI can generate productivity gains. In Pakistan, these benefits can emerge through applications of AI in financial services, agriculture, digital commerce, public administration, telecommunications, and other increasingly technology-intensive activities. The result, therefore, provides empirical support for H1, which proposes that artificial intelligence positively affects economic performance in Pakistan.

Digitalization also produces a positive coefficient ($\beta = 0.518$) and is statistically significant at the 10% level. This indicates that improvements in digital connectivity contribute positively to economic performance, although the magnitude of statistical evidence is weaker than that observed for AI. Digitalization can stimulate economic activity by lowering search and transaction costs, improving information flows, facilitating digital payments and financial inclusion, connecting businesses with larger markets, and increasing the efficiency of service delivery. These mechanisms are consistent with Goldfarb and Tucker (2019), who emphasize the ability of digital technologies to reduce several forms of economic costs, and with earlier empirical evidence demon-

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strating positive growth effects from telecommunications and broadband infrastructure (Röller & Waverman, 2001; Czernich et al., 2011). Myovella et al. (2020) similarly report that digitalization contributes to economic growth, although the magnitude of the benefits depends on countries' complementary capabilities. For Pakistan, the expansion of internet connectivity, e-commerce, digital banking, mobile financial services, and technology-based business activities provides plausible channels through which digitalization can improve aggregate economic performance. Accordingly, the findings support H2, which predicts a positive effect of digitalization on economic performance.

In contrast, cybersecurity has a negative and statistically significant coefficient ($\beta = -0.241$, $p < 0.10$). This result indicates that cybersecurity regulation or preparedness may impose short-term economic costs even as it contributes to a more secure digital environment. Stronger cybersecurity requirements can compel firms and public institutions to invest in security infrastructure, compliance systems, monitoring, reporting, skilled personnel, and data protection mechanisms. These expenditures may initially divert resources from other productive activities, particularly in developing economies where firms face financial and technological constraints. This interpretation is consistent with the broader law-and-economics argument that regulation can correct market failures but simultaneously generate compliance costs. It is also compatible with Jin et al. (2025), who find that cybersecurity law can constrain corporate investment through financing constraints and increased perceived risks. Importantly, the negative direct coefficient should not necessarily be interpreted as evidence that cybersecurity regulation is economically undesirable, because its economic benefits may operate indirectly by improving the returns generated by AI and digitalization, as examined subsequently in the moderation model. Nevertheless, because H3 predicts a positive direct effect of cybersecurity regulation on economic performance, H3 is not supported by the baseline findings.

The control variables provide additional insights into Pakistan's economic performance. FDI has a positive and statistically significant coefficient ($\beta = 0.332$, $p < 0.05$), suggesting that foreign investment contributes to economic activity through capital inflows, technology transfer, managerial knowledge, and integration into international production networks. GFCF is also positive ($\beta = 1.346$, $p < 0.10$), reinforcing the importance of domestic capital accumulation and productive investment for expanding economic capacity. Trade openness yields a positive and significant coefficient ($\beta = 0.282$, $p < 0.05$), indicating that greater international economic integration can support Pakistan's performance by expanding market access, facilitating the import of technologies and intermediate inputs, and strengthening competitive pressures. Taken together, these controls suggest that the economic returns from technological development occur alongside broader processes of investment, capital formation, and international integration.

Finally, the error-correction term is negative and highly significant ($ECT = -0.644$, $p < 0.01$), providing evidence of adjustment toward long-run equilibrium following short-run disturbances. The coefficient indicates that approximately 64.4% of disequilibrium is corrected within one year, implying a relatively rapid adjustment process. Thus, when Pakistan's economic performance deviates from the equilibrium relationship implied by AI, digitalization, cybersecurity, investment, and trade conditions, a substantial proportion of that deviation is corrected during the subsequent period. The negative and statistically significant ECT, therefore, strengthens the evidence for a stable dynamic relationship among the variables.

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Table 5: Main ARDL Results

Variables	Coefficient	Std. Error	t-statistic
Constant	16.699**	3.074	2.179
EP(-1)	0.109	0.246	0.441
ln(AI)	0.864***	0.267	3.227
ln(DIG)	0.518*	0.285	1.813
ln(CYB)	-0.241*	0.117	-2.053
ln(FDI)	0.332**	0.152	2.183
ln(GFCF)	1.346*	0.765	1.759
ln(TROP)	0.282**	0.119	2.362
ECT	-0.644***	0.206	3.122

Note: levels of significance are: * as 10%, ** as 5%, and *** as 1%

Table 6 provides particularly important findings because it examines the study's central law-and-economics proposition: whether cybersecurity regulation affects the economic returns generated by AI and digitalization. The interaction between AI and cybersecurity is positive and highly statistically significant ($\beta = 0.318$, $p < 0.01$). This indicates that stronger cybersecurity conditions enhance the positive relationship between AI and economic performance. Economically, AI systems depend heavily on data, interconnected digital infrastructure, cloud services, and information exchange. Weak cybersecurity can increase the expected costs of adopting these technologies through data breaches, system manipulation, privacy violations, and operational disruptions. Stronger cybersecurity governance can reduce these risks, improve confidence in AI-intensive activities, and provide clearer responsibilities for firms and institutions. This interpretation is consistent with institutional theory (North, 1990), which holds that effective institutions reduce uncertainty and improve the environment for productive economic activity. It also complements Filippucci et al. (2024), who emphasize that the productivity gains generated by AI depend on complementary institutional and policy conditions. Thus, cybersecurity appears to function not merely as a protective mechanism but as an institutional complement that increases the economic value of AI adoption. Consequently, H4 is supported: cybersecurity positively moderates the relationship between artificial intelligence and economic performance in Pakistan.

The interaction between digitalization and cybersecurity is likewise positive and highly significant ($\beta = 0.437$, $p < 0.01$), and its magnitude is larger than the AI interaction effect. This finding demonstrates that cybersecurity strengthens the contribution of digitalization to Pakistan's economic performance. Digital technologies reduce conventional transaction costs, but increasing digital dependence simultaneously creates new costs associated with cybercrime, fraud, information theft, data breaches, and service disruption. Effective cybersecurity regulation can reduce these expected costs by establishing security standards, defining institutional responsibilities, establishing incident-management mechanisms, and providing greater legal certainty. As a result, businesses and consumers may be more willing to engage in online transactions, digital financial services, e-commerce, and other technology-enabled activities. The result is consistent with Jin et al. (2025), who find that cybersecurity regulation can facilitate corporate digital transformation, and it reinforces the institutional argument that digital infrastructure produces larger economic benefits when accompanied by an effective governance environment. Therefore, H5 is strongly supported: cybersecurity regulation positively moderates the relationship between digitalization and economic performance in Pakistan.

An important finding emerges when the direct and moderating effects of cybersecurity are considered jointly. Cybersecurity itself has a small negative direct coefficient in the moderation model ($\beta = -0.027$, $p < 0.10$), while both interaction coefficients are strongly positive. This suggests that the economic value of cybersecurity regulation in Pakistan may be primarily complementary rather than independently growth-generating. Cybersecurity requirements can initially impose regulatory, compliance, and infrastructure costs, explaining the negative direct effect. However, when combined with AI and digitalization, the same regulatory environment can increase the economic returns from technological adoption by reducing cyber risks and strengthening digital trust. This distinction helps reconcile the apparently negative direct cybersecurity result with the strongly positive interaction effects and constitutes an important contribution of the study. Rather than assuming that cybersecurity regulation automatically increases economic growth, the findings suggest that its principal economic contribution may lie in creating the institutional conditions under which AI and digital technologies can be used more securely and productively.

Overall, the results support H1, H2, H4, and H5, but not H3. The central contribution is therefore not simply that AI and digitalization improve Pakistan's economic performance, but that cybersecurity regulation significantly strengthens both technological channels despite carrying a negative direct economic effect. This provides a particularly useful Law-and-Economics finding: cybersecurity regulation may entail immediate compliance and institutional costs, yet simultaneously function as an enabling legal infrastructure that improves the economic returns from technological transformation.

Table 6: Moderating Effect

Variables	Coefficient	Std. Error	t-statistic
Constant	0.923**	0.407	2.264
EP(-1)	0.233	0.257	0.906
ln(AI)	0.416***	0.151	2.737
ln(DIG)	0.749**	0.344	2.174
ln(CYB)	-0.027*	0.016	-1.643
AI*CYB	0.318***	0.083	3.795
DIG*CYB	0.437***	0.091	4.756

Conclusion and Recommendations

This study examined the effects of artificial intelligence, digitalization, and cybersecurity regulation on economic performance in Pakistan, with particular attention to whether cybersecurity regulation conditions the economic benefits of technological transformation. Using annual data from 2000 to 2025 and an ARDL framework, the findings demonstrate that artificial intelligence contributes positively and significantly to economic performance, indicating that AI-related technological capabilities can improve efficiency, innovation, and resource allocation. Digitalization also exerts a positive effect, highlighting the economic importance of expanding digital connectivity and technology-enabled activities. Among the control variables, foreign direct investment, gross fixed capital formation, and trade openness positively influence economic performance, reinforcing the complementary roles of foreign capital, domestic investment, and international economic integration. In contrast, cybersecurity regulation exhibits a negative direct effect.

This finding suggests that strengthening cybersecurity may initially impose compliance, infrastructure, administrative, and adjustment costs on firms and institutions. The significant error-correction term further confirms a stable adjustment toward the long-run equilibrium.

More importantly, the moderation analysis provides evidence that the economic role of cybersecurity regulation extends beyond its direct effect. The positive and significant interaction between AI and cybersecurity indicates that stronger cybersecurity conditions increase the economic returns associated with AI. Similarly, the positive interaction between digitalization and cybersecurity demonstrates that a more secure regulatory environment strengthens the contribution of digital transformation to economic performance. These findings suggest that cybersecurity regulation functions as a complementary institutional mechanism: although regulation may generate short-term compliance costs, it can simultaneously reduce technological risks, strengthen digital trust, and improve the environment in which AI and digital technologies contribute to economic activity.

The findings have important policy implications for Pakistan. Policymakers should pursue AI development, digitalization, and cybersecurity governance as interconnected components of economic policy rather than as separate policy domains. Investment in digital infrastructure, AI capabilities, skills development, and technology adoption should therefore be accompanied by an effective and adaptive cybersecurity regulatory framework. At the same time, cybersecurity requirements should be designed proportionately to avoid excessive compliance burdens, particularly for SMEs and emerging digital businesses. Regulatory simplification, technical assistance, cybersecurity capacity building, and clear compliance standards can reduce these adjustment costs. Pakistan should also strengthen institutional coordination among technology, economic, financial, and cybersecurity authorities, and promote secure digital infrastructure, data protection, cyber risk management, and public-private cooperation. Such an integrated approach can enable Pakistan to capture the productivity and growth opportunities offered by AI and digitalization while ensuring that cybersecurity regulation operates as an enabling foundation for sustainable digital economic transformation.

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