SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

Metaverse-Enabling Digital Infrastructure and Logistics Performance in BRICS Economies

Ayşe Güngör

Assistant Professor, Giresun University, Kadir Karabaş School of Applied Sciences, Department of Logistics Management, Türkiye.

Corresponding Email: ayse.gungor@giresun.edu.tr

ORCID: 0009-0006-3916-9657

Abstract. This study examines the associations between metaverse-enabling digital infrastructure and logistics performance across five BRICS economies: Brazil, China, India, Russia, and South Africa. To capture foundational digital conditions that may support metaverse-related logistics applications, a Metaverse-Enabling Digital Infrastructure Index (MEDII) is constructed from standardized indicators of internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. The analysis spans seven Logistics Performance Index reporting years—2007, 2010, 2012, 2014, 2016, 2018, and 2023—and comprises 35 country-year observations. The empirical strategy combines descriptive statistics, Pearson correlations, pooled ordinary least squares, country fixed effects, and two-way fixed effects. Although country fixed effects models indicate a positive association between MEDII and logistics performance, this relationship becomes statistically insignificant after controlling for common year effects. The principal two-way fixed-effects estimates therefore provide no robust evidence of a persistent association between MEDII and logistics performance. Robustness tests using a connectivity-only index, principal-component weighting, an additional R&D control, and leave-one-country-out estimations yield the same conclusion regarding statistical insignificance, although coefficient direction and magnitude show some sensitivity to specification and country composition. The findings highlight the importance of common temporal developments and support a cautious, noncausal interpretation given the small sample size and remaining endogeneity concerns.

Keywords: Metaverse-Enabling Digital Infrastructure Index, LPI, BRICS economies, digital infrastructure.

1 Introduction

Digital transformation has become an important driver of economic restructuring, competitiveness, and supply chain modernization. Within this broader transformation, the metaverse has emerged as a multidimensional digital ecosystem combining immersive environments, artificial intelligence, digital twins, blockchain, cloud and edge computing, extended reality, the Internet of Things, and advanced connectivity. Rather than representing a single technology, the metaverse depends on several interconnected technological and infrastructural layers. These include reliable internet access, broadband capacity, mobile connectivity, data-processing capabilities, interoperable digital platforms, and secure digital service environments. Similarly, evidence from other technology-intensive sectors indicates that the effective adoption of AI-, IoT-, and data-driven systems depends on adequate infrastructure, investment capacity, digital capabilities, and supportive policy conditions [1].

The potential relevance of the metaverse extends beyond entertainment, gaming, and social interaction. Metaverse-related technologies may support business operations, manufacturing, logistics, marketing, circular economy practices, and supply chain management. In logistics and supply chain contexts, applications such as digital twins, real-time monitoring, virtual simulation, warehouse optimization, route planning, predictive maintenance, and data-driven coordination may improve operational visibility and decision-making. Related research on smart city development also illustrates how connectivity, data systems, and digitally coordinated infrastructure can support broader urban and regional transformation [2][3]. However, the deployment of these applications depends on the presence of adequate digital infrastructure. Countries with stronger connectivity and digital service capacity may therefore be better positioned to adopt advanced digitally enabled logistics solutions.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

This issue is particularly relevant for emerging economies, which often display substantial differences in digital access, logistics capacity, innovation systems, institutional conditions, and investment resources. Moreover, these economies are increasingly integrated into global trade, digital services, and international supply chains. The original five BRICS economies—Brazil, China, India, Russia, and South Africa—provide an important empirical setting because they are large emerging markets with considerable economic, technological, and logistical heterogeneity. Their differences in connectivity, income levels, trade openness, investment patterns, and logistics performance offer a useful context for examining whether foundational digital infrastructure is associated with national logistics outcomes.

Logistics performance is an important component of international competitiveness and economic integration. Efficient logistics systems can reduce transaction costs, improve trade flows, strengthen supply chain reliability, and facilitate access to global markets. Nevertheless, logistics performance is shaped by a wide range of factors, including transport infrastructure, customs efficiency, institutional quality, geographical conditions, investment capacity, and technological capabilities. Previous comparative research has indicated that logistics development depends not only on geographical advantages but also on the capacity and effective utilization of roads, railways, ports, and related transportation infrastructure [4]. Logistics transformation is also connected with broader economic, energy, and environmental conditions, indicating that logistics outcomes emerge from the interaction of multiple structural factors [5]. As logistics operations become increasingly data intensive and connected to digital platforms, digital infrastructure may play a growing role in enabling new forms of monitoring, simulation, coordination, and automation. Its contribution, however, is unlikely to operate independently of broader country-specific and time-specific conditions.

Despite the expanding literature on metaverse, digital twins, blockchain, sustainability, and digital transformation, empirical evidence connecting the infrastructural foundations of metaverse-related applications to national logistics performance remains limited. Much of the existing research is conceptual, sector specific, or focused on individual technologies. Relatively few studies have examined whether country-level digital infrastructure conditions are associated with logistics performance across emerging economies. This gap is especially relevant in the BRICS context, where both digital transformation and logistics modernization are strategically important but develop unevenly.

This study addresses this gap by constructing a metaverse-enabling digital infrastructure index (MEDII) and examining its association with logistics performance in the original five BRICS economies. The MEDII is not intended to measure actual metaverse adoption or provide a comprehensive index of national metaverse readiness. Direct and consistently available country-level indicators of technologies such as extended reality, artificial intelligence, blockchain, digital twins, cloud infrastructure, edge computing, and Internet of Things deployment are not available for all countries and years included in the study. The index therefore captures selected foundational digital conditions that may support the implementation of metaverse-related logistics applications.

This study develops the Metaverse-Enabling Digital Infrastructure Index (MEDII) by aggregating four standardized indicators: internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. The first three indicators represent domestic connectivity and access capacity, whereas ICT service exports reflect a broader dimension of digital service capability and specialization. Because this latter indicator may not represent the same underlying connectivity dimension as the other components do, the study also evaluates a connectivity-only version of the index and a principal-component-based alternative. These robustness analyses allow the sensitivity of the results to index composition and weighting to be assessed.

The empirical analysis covers Brazil, China, India, Russia, and South Africa over seven Logistics Performance Index reporting years: 2007, 2010, 2012, 2014, 2016, 2018, and 2023. The final dataset contains 35 country-year observations. The analysis combines descriptive statistics, Pearson correlation analysis, pooled ordinary least squares regression, country fixed-effects models, and two-way fixed-effects models. The principal specification includes both country and year fixed effects to account for time-invariant national characteristics and common temporal developments. Additional controls include exports as a percentage of GDP, log real GDP per capita, gross fixed capital formation, and, in a supplementary specification, R&D expenditure.

The study contributes to literature in three respects. First, it introduces a metaverse-enabling digital infrastructure perspective into the empirical analysis of logistics performance while avoiding the stronger claim that conventional connectivity indicators directly measure metaverse adoption. Second, it develops a transparent, standardized composite index and evaluates its sensitivity to the exclusion of ICT service exports and to principal-component weighting. Third, it provides evidence from a small but strategically important group of emerging economies and explicitly evaluates the sensitivity of the findings through additional controls and leave-one-country-out estimations.

The empirical findings indicate that the relationship between the MEDII and logistics performance is sensitive to the treatment of common time effects. Although country fixed-effects models suggest a positive association, this relationship does not remain statistically significant in the principal two-way fixed-effects specifications.

Alternative index constructions and supplementary sensitivity analyses similarly provide no robust evidence of a statistically significant association.

These findings contribute to the literature by demonstrating the importance of distinguishing country-specific variation from common temporal developments when examining digital infrastructure and logistics performance. Given the limited sample size and the observational nature of the data, the results are interpreted as conditional associations rather than causal effects.

2 Literature Review

2.1 Metaverse and Enabling Digital Infrastructure

The metaverse is generally understood as an interconnected digital ecosystem in which physical and virtual environments are integrated through immersive, persistent, and interactive technologies. Rather than representing a single technology, it depends on a combination of extended reality, artificial intelligence, blockchain, computer vision, the Internet of Things, robotics, cloud and edge computing, and advanced mobile networks. Lee et al. (2024) identify these technologies as key components of metaverse ecosystems. The implementation of such technologies requires reliable digital infrastructure. Immersive and data-intensive applications depend on internet access, high-capacity broadband, mobile connectivity, data-processing systems, interoperable digital platforms, and secure digital environments. Basic connectivity does not itself constitute the metaverse, but it provides some of the foundational conditions required for advanced applications to be deployed.

This distinction is particularly important in emerging economies, where technological adoption is shaped by infrastructure gaps, investment capacity, institutional conditions, market maturity, and innovation systems. Dakduk et al. (2024) emphasize the growing importance of Web3, e-commerce, innovation ecosystems, and digital transformation in emerging markets. Similarly, Vaz (2024) highlights the role of knowledge structures, technology, geography, and regional innovation systems in shaping digital development.

Accordingly, country-level metaverse readiness cannot be reduced to internet access alone. Advanced applications also require cloud capacity, computing power, cybersecurity, digital skills, organizational readiness, and direct investment in technologies such as digital twins, artificial intelligence, and IoT systems. Nevertheless, connectivity and digital service indicators can provide information about the broader environment in which these applications may develop.

2.2 Digital Technologies and Logistics Performance

Metaverse-related technologies may have important implications for logistics and supply chain management. Digital twins, IoT devices, artificial intelligence, cloud platforms, and immersive environments can support shipment monitoring, warehouse simulation, route optimization, predictive maintenance, inventory planning, and supply chain coordination. These applications may improve visibility, information exchange, and operational decision-making.

Digital twins are especially relevant because they create virtual representations of physical assets, processes, and infrastructure. Jebbor et al. (2025) argued that the integration of digital twins and metaverse technologies can support sustainable circular operations through improved monitoring, prediction, simulation, and resource optimization. In logistics, digital twins may allow firms to evaluate warehouse layouts, track transport activities, identify disruptions, and test alternative operational scenarios before implementing them in physical systems.

Blockchain is also frequently associated with metaverse ecosystems. It may support smart contracts, traceability, authentication, secure transactions, and decentralized information exchange. These functions are relevant to logistics networks in which multiple participants must share reliable information about products, shipments, payments, and ownership. However, blockchain adoption depends on interoperability, regulation, data governance, organizational cooperation, and sufficient technological infrastructure.

The relationship between digital transformation and sustainability has also received increasing attention. Agrawal and Bansal (2025) suggest that metaverse-related digital ecosystems may contribute to business resilience and sustainable development. Similarly, Danil et al. (2025) emphasize the role of technological innovation in supporting productivity, competitiveness, and sustainable economic growth. These studies indicate that metaverse-related technologies should be considered part of a broader digital innovation system rather than isolated technological tools.

Nevertheless, digital infrastructure alone may not automatically improve logistics performance. National logistics outcomes are also influenced by transportation networks, customs efficiency, institutional quality, geographical conditions, investment capacity, trade integration, and workforce capabilities. Digital connectivity may complement these factors, but its contribution depends on the adoption of logistics-specific technologies and organizational transformation.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

The relationship may also operate in both directions. Countries with stronger logistics systems may have greater resources and incentives to invest in digital infrastructure. This possibility creates potential reverse causality and makes it necessary to distinguish statistical associations from causal impacts.

2.3 Research Gap and Conceptual Scope of MEDII

Despite the expanding literature on metaverse, digital twins, blockchain, sustainability, and digital transformation, limited empirical evidence exists on the relationship between metaverse-enabling infrastructure and logistics performance at the country level. Existing studies have focused mainly on conceptual frameworks, firm-level applications, individual technologies, marketing, sustainability, or financial markets. Cross-country evidence from emerging economies remains comparatively limited.

This gap is particularly relevant for Brazil, China, India, Russia, and South Africa. These economies differ substantially in terms of digital connectivity, income, trade openness, investment, innovation capacity, and logistics performance. Their heterogeneity provides an informative setting for examining whether foundational digital conditions are associated with national logistics outcomes.

To address this gap, this study develops the Metaverse-Enabling Digital Infrastructure Index (MEDII) by combining four standardized indicators: internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. The underlying indicators are obtained from established international data sources, whereas their selection, standardization, equal weighting, and aggregation constitute the index-construction procedure proposed in this study.

The MEDII is not intended to measure actual metaverse adoption or provide a comprehensive measure of national metaverse readiness. It does not directly capture extended reality, artificial intelligence, blockchain, digital twins, cloud infrastructure, edge computing, or IoT deployment. Instead, it measures selected foundational digital conditions that may facilitate the implementation of metaverse-related logistics applications.

Internet usage represents participation in digital networks, fixed broadband subscriptions reflect access to relatively stable and high-capacity connectivity, and mobile cellular subscriptions capture the reach of mobile communication systems. ICT service exports represent a broader dimension of digital service capability and specialization. Because ICT service exports may differ conceptually from domestic connectivity, the study also estimates a connectivity-only index that excludes this indicator.

In addition, principal component analysis is used as an alternative weighting procedure. This allows the study to evaluate whether the empirical results depend on the equal-weighting method or on the inclusion of ICT service exports. The novelty of MEDII therefore does not arise from claiming that its components are uniquely specific to the metaverse. Rather, it combines observable digital infrastructure indicators within a transparent framework and applies them to the study of logistics performance from a metaverse-enabling perspective.

Overall, the literature supports three main conclusions. First, the metaverse is an infrastructure-dependent digital ecosystem rather than a standalone technology. Second, technologies such as digital twins, artificial intelligence, blockchain, IoT, and cloud computing may support logistics operations, but their adoption requires broader technological, organizational, and institutional capabilities. Third, foundational digital infrastructure may facilitate logistics digitalization, although it is neither a complete measure of metaverse readiness nor sufficient by itself to improve national logistics performance.

Based on this framework, the present study examines whether MEDII is associated with logistics performance in the original five BRICS economies. Given the observational nature of the data and the limited sample, the analysis evaluates conditional associations rather than claiming a causal effect.

3 Methodology

3.1 Research Design

This study examines whether metaverse-enabling digital infrastructure is associated with logistics performance in the original five BRICS economies. A quantitative research design was adopted, and panel data methods were employed to analyze country–year observations. The empirical procedure combines descriptive statistics, Pearson correlation analysis, pooled ordinary least squares regression, country fixed effects estimation, and two-way fixed effects estimation.

Logistics performance is treated as the dependent variable. The Metaverse-Enabling Digital Infrastructure Index (MEDII) is included as the main explanatory variable. The principal specifications additionally control for trade openness, economic development, and domestic investment via exports as a percentage of GDP, the natural logarithm of real GDP per capita, and gross fixed capital formation as a percentage of GDP. Research and development expenditures are introduced separately in a supplementary robustness specification because two observations are missing.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

The study does not seek to estimate a causal effect of digital infrastructure on logistics performance. Instead, the estimated coefficients are interpreted as conditional associations after accounting for observable control variables, time-invariant country characteristics, and common year-specific developments.

3.2 Sample and Dataset

The sample consists of Brazil, China, India, Russia, and South Africa. The analysis covers seven years—2007, 2010, 2012, 2014, 2016, 2018, and 2023—selected according to the availability of the World Bank Logistics Performance Index. The resulting dataset contains 35 country-year observations, corresponding to five countries observed over seven LPI reporting years.

Although the dataset is balanced across countries, the time intervals between observations are irregular because the LPIs are not published annually. This characteristic limits the use of conventional annual dynamic-panel and lagged-variable procedures.

The logistics performance data were obtained from the World Bank Logistics Performance Index, whereas the digital infrastructure and macroeconomic variables were compiled from the World Development Indicators. The dependent variable is the overall logistics performance index. The digital infrastructure indicators include internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports.

Exports as a percentage of GDP, log real GDP per capita, and gross fixed capital formation were used as economic control variables. R&D expenditures were available for 33 observations because of two missing country-year values. It was therefore excluded from the principal specifications and used only in a supplementary robustness model.

3.3 Variables

3.3.1 Dependent Variable

The dependent variable is the overall logistics performance index. Higher LPI values indicate stronger national logistics performance.

The LPI is based partly on expert assessments and is available only for selected years. Consequently, it should be interpreted as a broad indicator of perceived national logistics performance rather than as a purely objective measure of individual logistics outcomes.

3.3.2 Main Explanatory Variables

The main explanatory variable is the Metaverse-Enabling Digital Infrastructure Index. The MEDII does not measure actual metaverse adoption or provide a comprehensive measure of national metaverse readiness. Direct indicators of technologies such as extended reality, digital twins, blockchain, cloud computing, edge computing, artificial intelligence, and Internet of Things deployment are not consistently available for the selected countries and periods.

MEDII therefore captures selected foundational digital conditions that may support the implementation of data-intensive, interconnected, immersive, and digitally coordinated logistics applications. The index should be interpreted as a measure of metaverse-enabling digital infrastructure rather than as a direct measure of metaverse technology adoption.

MEDII comprises the following indicators:

a. Internet usage as a percentage of the population
b. Fixed broadband subscriptions
c. Mobile cellular subscriptions
d. ICT service exports

Internet usage, fixed broadband subscriptions, and mobile cellular subscriptions represent domestic connectivity and access capacity. ICT service exports capture a broader digital service specialization dimension. Because ICT service exports may differ conceptually and empirically from domestic connectivity, the robustness analysis also estimates an alternative index excluding this component.

3.3.3 Control variables

Exports as a percentage of GDP are used to represent trade openness and international economic integration. Countries with greater exposure to international trade may face greater demand for efficient transport, customs, and logistics services.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

The natural logarithm of real GDP per capita is included to control for differences in economic development. Higher-income economies may possess greater financial and institutional capacity to invest in both logistics systems and digital infrastructure.

Gross fixed capital formation as a percentage of GDP is used as a measure of domestic investment and physical capital accumulation. It captures investment conditions that may influence transport networks, storage facilities, and other infrastructure relevant to logistics performance.

R&D expenditure as a percentage of GDP is used only in a supplementary specification as an indicator of national innovation capacity. Because R&D expenditure and gross fixed capital formation are relatively strongly correlated and the sample is small, they are not included together in the supplementary model.

3.4 Construction of the Metaverse-Enabling Digital Infrastructure Index

The four MEDII components are reported in different units and ranges. Direct aggregation could therefore cause indicators with larger numerical scales or greater dispersion to exert disproportionate influence on the index. Each component was consequently standardized via the z-score transformation:

$$Z_{kit} = \frac{X_{kit} - \bar{X}_k}{s_k}$$

where X_{kit} denotes the value of indicator k for country i in year t, $\bar{X}_k$ is the sample mean of indicator k, and s_k is its sample standard deviation.

The baseline MEDII was calculated as the arithmetic mean of the four standardized indicators:

$$MEDII_{it} = \frac{ZInternet_{it} + ZBroadband_{it} + ZMobile_{it} + ZICTService_{it}}{4}$$

Equal weights were assigned to the four components. This approach was selected because it is transparent, easily replicable, and does not impose an unsupported theoretical hierarchy among the indicators. A higher MEDII value indicates stronger metaverse-enabling digital infrastructure relative to the sample mean. Because the index is constructed from standardized variables, its mean is approximately zero.

Two alternative index specifications were estimated to evaluate the sensitivity of the results to the composition and weighting of MEDII.

First, a connectivity-only MEDII was constructed by excluding ICT service exports:

$$MEDII_{it}^{Connectivity} = \frac{ZInternet_{it} + ZBroadband_{it} + ZMobile_{it}}{3}$$

Second, principal component analysis was applied to the four standardized indicators. The score of the first principal component was used as a statistically weighted alternative to the equally weighted MEDII. This procedure allows the contribution of each component to be determined by the covariance structure of the data rather than by predetermined equal weights.

These alternative measures were not intended to redefine the conceptual meaning of the index. They were used to determine whether the regression findings were driven by the inclusion of ICT service exports or by the equal-weighting procedure.

3.5 Model Specification

The pooled OLS specification is expressed as:

$$LPI_{it} = \beta_0 + \beta_1 MEDII_{it} + \gamma' X_{it} + \varepsilon_{it}$$

where LPI_{it} represents the logistics performance of country i in year t, $MEDII_{it}$ represents the metaverse-enabling digital infrastructure, and X_{it} denotes the vector of control variables. Depending on the specification, the control vector includes exports as a percentage of GDP, log real GDP per capita, and gross fixed capital formation.

The country fixed-effects model is specified as follows:

$$LPI_{it} = \beta_1 MEDII_{it} + \gamma' X_{it} + \alpha_i + \varepsilon_{it}$$

where $\alpha_i$represents unobserved country-specific characteristics that remain constant over time. These characteristics may include geographical conditions, historical logistics capacity, legal traditions, institutional structures, and persistent features of national infrastructure systems.

The principal empirical specification is the two-way fixed-effects model:

$$LPI_{it} = \beta_1 MEDII_{it} + \gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it}$$

where $\lambda_t$represents year fixed effects. The year effects account for common developments affecting all five countries in a particular LPI reporting year, including global economic conditions, technological change, international trade disruptions, and changes in the broader logistics environment.

The baseline two-way fixed-effects model includes MEDII, exports as a percentage of GDP, and log real GDP per capita. An extended specification additionally includes gross fixed capital formation. Alternative two-way fixed-effects models replace the original MEDII with connectivity-only and PCA-weighted indices.

A supplementary two-way fixed-effects specification adds R&D expenditure to the baseline model:

$$LPI_{it} = \beta_1 MEDII_{it} + \beta_2 ExportsGDP_{it} + \beta_3 \ln GDPpc_{it} + \beta_4 R\&D_{it} + \alpha_i + \lambda_t + \varepsilon_{it}$$

Because the R&D model is estimated via 33 observations, it is interpreted as supplementary evidence rather than as the principal specification.

The coefficient β_1 measures the within-country association between the MEDII and logistics performance after accounting for the included controls and fixed effects. It should not be interpreted as a causal effect.

3.6 Analysis Procedure

The empirical analysis was conducted in several stages. First, descriptive statistics were calculated for all the variables. The number of observations and the minimum, maximum, mean, and standard deviation values were reported to evaluate the distributions and cross-country variations in the data.

Second, pairwise Pearson correlation coefficients were calculated to examine the direction and strength of the bivariate relationships among LPI, MEDII, the individual digital infrastructure indicators, and the control variables. Correlations involving R&D expenditure were calculated via the 33 available observations.

Third, pooled OLS models were estimated as preliminary specifications. Heteroskedasticity-robust standard errors were used in the pooled OLS estimations. The models were estimated sequentially by first including the MEDII and exports as a percentage of GDP, then adding log real GDP per capita, and finally adding gross fixed capital formation.

Variance inflation factors were calculated to assess multicollinearity among the explanatory variables. The low VIF values indicated that multicollinearity was not a substantial concern in the estimated models.

Fourth, country fixed effects models were estimated to control for time-invariant national characteristics. The specifications were expanded sequentially by adding log real GDP per capita and gross fixed capital formation.

Fifth, two-way fixed effects models were estimated by including both country and year fixed effects. The joint statistical significance of the year dummy variables was evaluated via Wald-type joint significance tests. The two-way fixed-effects specification was treated as the principal panel model because unobserved national characteristics are plausibly correlated with digital infrastructure and economic development. In addition, the joint significance of the year effects indicates that common temporal developments should not be omitted.

Random-effects estimation was not used as the principal basis for inference because its identifying assumption requires unobserved country-specific effects to be uncorrelated with the explanatory variables. This assumption is difficult to justify for BRICS economies, where persistent institutional, economic, geographical, and infrastructure characteristics are likely related to both digital infrastructure and logistics performance. Accordingly, the revised analysis does not rely on Hausman test-based selection of the random effects model.

Sixth, several robustness and sensitivity analyses were conducted. The two-way fixed-effects model was re-estimated via connectivity-only MEDII and the PCA-weighted MEDII to assess sensitivity to index composition and weighting. R&D expenditure was introduced as an additional control in a supplementary model.

A leave-one-country sensitivity analysis was also conducted. The principal two-way fixed-effects specification was re-estimated five times, excluding one BRICS country in each iteration. This procedure was used to determine whether the results were disproportionately influenced by a single economy.

The number of observations was determined by the fixed sample of the original five BRICS economies and the availability of LPI reporting years. An ex ante power analysis was therefore not used to define the sample size. Instead, confidence intervals, alternative index constructions, additional controls, and leave-one-country-out estimates were used to assess the uncertainty and sensitivity of the results. These procedures improve the transparency of small-sample analysis but do not eliminate the limitations associated with low statistical power.

Finally, the available data do not permit a fully satisfactory treatment of endogeneity. A correctly aligned one-year-lagged MEDII could not be constructed because annual observations for all index components were not consistently available for the years immediately preceding each LPI observation. The small number of countries also makes the dynamic panel GMM unsuitable, but no theoretically credible and empirically available instrumental variables can be identified. The results are therefore presented as conditional associations, and potential reverse causality, simultaneity, and residual omitted-variable bias are acknowledged as limitations.

4 Results and Discussion

Table 1. Descriptive Statistics of the Variables

Variable	N	Min.	Max.	Mean	Std. Dev.
Logistics Performance Index (LPI)	35	2.370	3.775	3.202	0.370
MEDII	35	−1.019	1.440	0.000	0.574
Internet Usage (%)	35	3.950	92.250	46.726	25.390

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

Fixed Broadband Subscriptions	35	0.260	44.730	10.229	10.261
Mobile Cellular Subscriptions	35	19.621	180.842	109.814	39.527
ICT Service Exports	35	1.916	48.169	14.321	16.435
Exports/GDP (%)	35	10.870	34.910	22.988	6.441
R&D Expenditure (% of GDP)	33	0.660	2.577	1.147	0.491
Log Real GDP per Capita	35	6.975	9.432	8.638	0.708
Gross Fixed Capital Formation (% of GDP)	35	14.935	43.874	26.057	9.714

Note: Due to the presence of two missing observations for the R&D expenditure variable, the sample size for this variable is N = 33. For all other variables, the sample size is N = 35.

Descriptive statistics were evaluated via 35-country-year observations from the five BRICS economies. The mean value of the logistic performance index (LPI) is 3.202, with a standard deviation of 0.370. The LPIs range from 2.370-3.775, indicating moderate variation in logistics performance across countries and years.

The Metaverse-Enabling Digital Infrastructure Index (MEDII), the main explanatory variable, was constructed as the arithmetic mean of the standardized values of internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. Its mean is approximately zero because the underlying components were standardized before aggregation. The MEDII ranges from -1.019 to 1.440, revealing considerable differences in foundational digital infrastructure capacity across the BRICS economies. However, the index should be interpreted as a measure of selected digital conditions that may enable metaverse-related applications rather than as a comprehensive measure of metaverse readiness.

The average internet usage rate is 46.726%, with values ranging from 3.950% to 92.250%, indicating substantial disparities in digital access. Fixed broadband subscriptions have a mean of 10.229 and range from 0.260-44.730. Mobile cellular subscriptions exhibit a substantially higher mean of 109.814, suggesting that mobile connectivity is considerably more widespread than fixed broadband infrastructure across the sample.

ICT service exports have a mean of 14.321 and a standard deviation of 16.435. The comparatively high dispersion indicates pronounced cross-country heterogeneity in digital service export capacity. While ICT services constitute a substantial share of service exports in some country-year observations, their contribution remains considerably lower in others.

Among the control variables, exports as a percentage of GDP have a mean of 22.988, with values ranging from 10.870-34.910, indicating differences in trade openness across the sample. The natural logarithm of real GDP per capita has a mean of 8.638 and a standard deviation of 0.708, reflecting substantial differences in economic development among the BRICS economies. Gross fixed capital formation averages 26.057% of GDP and ranges from 14.935% to 43.874%, suggesting considerable variation in domestic investment and physical capital accumulation.

The average R&D expenditure is 1.147% of GDP. However, because two observations are missing, this variable is available for only 33 country-year observations. It is therefore excluded from the principal regression specifications and used only in supplementary robustness analyses.

Overall, the descriptive statistics demonstrate substantial heterogeneity in logistics performance, digital connectivity, digital service capacity, economic development, trade openness, and capital formation across the BRICS economies. This variation provides an empirical basis for examining whether metaverse-enabling digital infrastructure is associated with logistics performance after accounting for selected economic and investment-related factors.

Table 2. Pearson Correlation Matrix

Variable	1	2	3	4	5	6	7	8	9	10
1. LPI	1.000									
2. MEDII	−0.056	1.000								
3. Internet Usage	−0.007	0.892**	1.000							
4. Fixed Broadband	0.010	0.802**	0.735**	1.000						
5. Mobile Subscriptions	−0.132	0.705**	0.759**	0.377*	1.000					
6. ICT Service Exports	0.002	−0.103	−0.447**	−0.270	−0.518**	1.000				

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

7. Exports/GDP	0.014	−0.069	−0.045	−0.201	0.200	−0.111	1.000			
8. Log GDP per Capita	−0.060	0.482**	0.719**	0.631**	0.642**	−0.885**	−0.062	1.000		
9. Gross Fixed Capital Formation	0.310	−0.069	−0.264	0.248	−0.534**	0.391*	0.018	−0.287	1.000	
10. R&D Expenditure	0.310	0.378*	0.379*	0.748**	−0.026	−0.240	−0.192	0.478**	0.650**	1.000

Note: Pairwise Pearson correlation coefficients are reported. Correlations involving R&D expenditure are based on 33 observations because of two missing values; all other correlations are based on 35 observations. * *$p < 0.05$; ** $p < 0.01$.*

The Pearson correlation results indicate that there is no statistically significant bivariate relationship between the Logistics Performance Index (LPI) and the Metaverse-Enabling Digital Infrastructure Index (MEDII) (r = -0.056, p = 0.752). This result suggests that no direct linear association between the two variables can be identified without accounting for country-specific characteristics, temporal patterns, or other economic factors.

Individual digital infrastructure indicators are also not significantly correlated with LPIs. The correlations of LPIs with internet usage (r = -0.007, p = 0.969), fixed broadband subscriptions (r = 0.010, p = 0.957), mobile cellular subscriptions (r = -0.132, p = 0.451), and ICT service exports (r = 0.002, p = 0.993) are statistically insignificant. Similarly, exports as a percentage of GDP and log GDP per capita do not show significant bivariate relationships with logistics performance.

Gross fixed capital formation is positively correlated with LPIs (r = 0.310, p = 0.070), but the relationship does not reach the conventional 5% significance threshold. R&D expenditure also has a positive but statistically insignificant correlation with LPIs (r = 0.310, p = 0.079). These coefficients nevertheless suggest that investment and innovation capacity may warrant consideration in multivariate models.

The MEDII is strongly and positively correlated with internet usage (r = 0.892, p < 0.01), fixed broadband subscriptions (r = 0.802, p < 0.01), and mobile cellular subscriptions (r = 0.705, p < 0.01). These results indicate that the index is closely associated with its three connectivity-related components. MEDII is also moderately and positively correlated with log GDP per capita (r = 0.482, p = 0.003), suggesting that countries with higher income levels generally possess stronger enabling digital infrastructure.

In contrast, ICT service exports are not significantly correlated with the MEDII (r = -0.103, p = 0.558). ICT service exports are negatively correlated with internet usage (r = -0.447, p = 0.007), mobile subscriptions (r = -0.518, p = 0.001), and log GDP per capita (r = -0.885, p < 0.01). These findings indicate that ICT service export capacity does not necessarily develop in parallel with domestic connectivity and income levels within the selected BRICS economies. This distinct correlation pattern also suggests that ICT service exports may represent a digital service specialization dimension rather than the same underlying connectivity dimension captured by the other MEDII components. Consequently, the sensitivity of the results to the exclusion or alternative weighting of ICT service exports is examined in the robustness analyses.

Log GDP per capita is strongly and positively correlated with internet usage (r = 0.719, p < 0.01), fixed broadband subscriptions (r = 0.631, p < 0.01), and mobile subscriptions (r = 0.642, p < 0.01). These relationships support the inclusion of economic development as a control variable because income differences may influence both digital infrastructure development and national logistics capacity.

R&D expenditure is positively correlated with MEDII (r = 0.378, p = 0.030), internet usage (r = 0.379, p = 0.030), fixed broadband subscriptions (r = 0.748, p < 0.01), log GDP per capita (r = 0.478, p = 0.005), and gross fixed capital formation (r = 0.650, p < 0.01). The relatively strong correlation between R&D expenditure and gross fixed capital formation suggests that these variables should be introduced separately in supplementary specifications to avoid excessive multicollinearity in a small sample.

Overall, the correlation analysis shows that the connectivity-related components of the MEDII are strongly interrelated, whereas ICT service exports display a different empirical pattern. None of the digital infrastructure indicators has a statistically significant direct correlation with logistics performance. Therefore, the subsequent regression analyses evaluate whether MEDII is associated with LPIs after accounting for trade openness, economic development, domestic investment, country-specific heterogeneity, and common time effects.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

Table 3. Pooled OLS Regression Results

Variable	Model 1	Model 2	Model 3
MEDII	−0.035	−0.022	−0.041
	(0.125)	(0.143)	(0.129)
Exports/GDP	0.001	0.001	0.000
	(0.010)	(0.010)	(0.010)
Log GDP per capita	—	−0.022	0.034
		(0.086)	(0.085)
Gross fixed capital formation	—	—	0.012**
			(0.006)
Constant	3.189***	3.382***	2.581***
	(0.197)	(0.814)	(0.781)
Observations	35	35	35
R^2	0.003	0.005	0.100
Adjusted R^2	−0.059	−0.092	−0.020
Robust F-statistic	0.046	0.072	3.002
Prob. > F	0.955	0.975	0.034

Note: The dependent variable is the logistics performance index. The heteroskedasticity-robust standard errors are reported in parentheses. Model 1 includes MEDII and trade openness. Model 2 additionally controls for log real GDP per capita. Model 3 additionally includes gross fixed capital formation. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$. Table 3 reports the pooled ordinary least squares (Pooled OLS) regression results for three alternative model specifications. Model 1 includes MEDII and trade openness (exports as a percentage of GDP). Model 2 additionally controls for the natural logarithm of real GDP per capita, whereas Model 3 further incorporates gross fixed capital formation to account for domestic investment and physical capital accumulation. Heteroskedasticity-robust standard errors are reported in all estimations.

The results indicate that MEDII is not statistically significantly associated with logistics performance in any of the three model specifications. In Model 1, the estimated coefficient of MEDII is negative but insignificant ($\beta = -0.035$, $p = 0.778$). Similarly, exports as a percentage of GDP do not exhibit a statistically significant relationship with the logistics performance index (LPI). The model explains only a negligible proportion of the variation in logistics performance ($R^2 = 0.003$) and is not statistically significant overall ($F = 0.046$, $p = 0.955$).

The inclusion of real GDP per capita in Model 2 does not materially alter the findings. The coefficient of MEDII remains statistically insignificant ($\beta = -0.022$, $p = 0.878$), and neither trade openness nor the level of economic development is significantly associated with LPI. Consistent with Model 1, the explanatory power of the model remains very limited ($R^2 = 0.005$).

In Model 3, gross fixed capital formation emerges as the only statistically significant explanatory variable ($\beta = 0.012$, $p = 0.034$), suggesting that higher levels of domestic investment are associated with improved logistics performance. Specifically, a one-percentage-point increase in gross fixed capital formation as a share of GDP is associated with an estimated 0.012-point increase in the Logistics Performance Index, with the remaining variables held constant. Despite this improvement, the MEDII coefficient remains statistically insignificant ($\beta = -0.041$, $p = 0.752$). The explanatory power of the model increases to $R^2 = 0.100$, and the overall model becomes statistically significant ($F = 3.002$, $p = 0.034$), although the adjusted R^2 remains slightly negative, indicating that the model continues to explain only a limited share of the cross-country variation in logistics performance.

Overall, the pooled OLS estimates provide no empirical evidence that the MEDII has a statistically significant effect on logistics performance. Instead, the findings suggest that domestic investment, as measured by gross fixed capital formation, is more closely associated with logistics performance than the digitalization indicator included in this study. Because pooled OLS does not control for unobserved country-specific heterogeneity, these findings should be interpreted with caution. The subsequent fixed-effects and random-effects panel estimations provide a more appropriate framework for assessing whether the relationship between MEDII and logistics performance persists after accounting for unobserved country-level characteristics.

Multicollinearity was assessed via variance inflation factors. In the specifications including MEDII, exports as a percentage of GDP, and log GDP per capita, the VIF values ranged from 1.01--1.31, with a mean VIF of 1.21. After gross fixed capital formation was added, the highest VIF was 1.42, and the mean VIF remained at 1.21. These values indicate that multicollinearity does not constitute a substantial concern in the estimated models.

Table 4. Fixed-Effects and Two-Way Fixed-Effects Results

Variable	**Model 1: FE**	**Model 2: FE**	**Model 3: FE**	**Model 4: TWFE**	**Model 5: TWFE**
MEDII	0.193***	0.148**	0.150**	−0.074	−0.088
	(0.044)	(0.064)	(0.065)	(0.111)	(0.112)
Exports/GDP	−0.005	0.001	0.002	−0.002	0.003
	(0.007)	(0.009)	(0.010)	(0.009)	(0.010)
Log GDP per capita	—	0.212	0.224	0.211	0.259
		(0.215)	(0.227)	(0.192)	(0.198)
Gross fixed capital formation	—	—	0.003	—	0.013
			(0.013)		(0.013)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	No	No	No	Yes	Yes
Observations	35	35	35	35	35
Number of countries	5	5	5	5	5
Within R^2	0.478	0.497	0.497	0.737	0.749
F-statistic	12.840	8.878	6.431	6.547	5.979
Model p value	<0.001	<0.001	0.001	<0.001	<0.001
Joint significance of year effects	—	—	—	0.022	0.019

Note: The dependent variable is the logistics performance index. Standard errors are reported in parentheses. FE refers to country fixed effects, whereas TWFE refers to country and year fixed effects. Model 1 presents the baseline country fixed-effects specification. Model 2 adds log real GDP per capita, and Model 3 additionally controls for gross fixed capital formation. Models 4 and 5 include both country and year fixed effects. **p** < 0.05; ***p*** < 0.01.

Table 4 reports the results of the country fixed-effects (FE) and two-way fixed-effects (TWFE) estimations. Models 1–3 control for unobserved time-invariant country-specific characteristics, whereas Models 4 and 5 additionally account for common year effects. This sequential specification allows an assessment of whether the relationship between MEDII and logistics performance remains robust after controlling for both country heterogeneity and time-specific shocks.

The country fixed effects results indicate a positive and statistically significant association between MEDII and logistics performance. In Model 1, the coefficient of MEDII is positive and highly significant ($\beta = 0.193$, $p < 0.001$), whereas exports as a percentage of GDP are not statistically significant. The model explains approximately 47.8% of the within-country variation in the Logistics Performance Index (Within $R^2 = 0.478$).

After controlling for the level of economic development in Model 2, the estimated coefficient of MEDII decreases to 0.148 but remains positive and statistically significant ($p = 0.028$). Neither exports as a percentage of GDP nor real GDP per capita exhibits a statistically significant within-country effect on logistics performance. In Model 3, the inclusion of gross fixed capital formation does not materially alter the results. MEDII continues to display a positive and statistically significant coefficient ($\beta = 0.150$, $p = 0.030$), whereas gross fixed capital formation remains statistically insignificant.

The findings change substantially once common year effects are incorporated. In the two-way fixed-effects specifications (Models 4 and 5), the coefficient of MEDII becomes negative and loses statistical significance ($\beta = -0.074$, $p = 0.510$ in Model 4; $\beta = -0.088$, $p = 0.438$ in Model 5). Similarly, exports as a percentage of GDP, real GDP per capita, and gross fixed capital formation remain statistically insignificant after controlling for both country and year fixed effects.

The joint significance tests confirm that the year fixed effects are statistically significant in both two-way fixed effects models (Model 4: $F(6,21) = 3.21$, $p = 0.022$; Model 5: $F(6,20) = 3.35$, $p = 0.019$). These results suggest that common temporal developments affecting all BRICS countries play an important role in explaining changes in logistics performance and should therefore be incorporated into the empirical specification.

Overall, the fixed-effects analysis indicates that the positive relationship between MEDII and logistics performance observed in the country fixed-effects models is not robust to the inclusion of year fixed effects. The disappearance of statistical significance after controlling for common time shocks suggests that the initial positive association may partly reflect shared temporal trends rather than an independent effect of MEDII. Consequently, the fixed-effects evidence does not provide robust support for a persistent relationship between MEDII and logistics performance once both unobserved country-specific heterogeneity and common year effects are taken into account.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

Table 5. Robustness Tests Using Alternative MEDII Specifications and Additional R&D Control

Panel A: Principal component analysis

Indicator	First-component coefficient
Internet usage	0.582
Fixed broadband subscriptions	0.465
Mobile cellular subscriptions	0.524
ICT service exports	−0.414
Eigenvalue of first component	2.588
Variance explained by first component	64.69%
Cumulative variance explained by first two components	84.86%

Panel B: Two-Way Fixed Effects Results

Statistic	Original MEDII	Connectivity-only MEDII	PCA-weighted MEDII
Digital infrastructure index	−0.074	−0.050	−0.029
	(0.111)	(0.093)	(0.065)
p value	0.510	0.595	0.661
Exports/GDP	−0.002	−0.002	−0.001
	(0.009)	(0.009)	(0.009)
Log GDP per capita	0.211	0.208	0.204
	(0.192)	(0.193)	(0.193)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	35	35	35
Number of countries	5	5	5
Within R^2	0.737	0.735	0.734
Joint p value of year effects	0.022	0.025	0.028

Panel C: Supplementary Two-Way Fixed-Effects Model Including R&D

Variable/Statistic	MEDII with R&D
MEDII	0.135
	(0.182)
p value	0.468
Exports/GDP	0.000
	(0.010)
Log GDP per capita	0.466
	(0.274)
R&D expenditure	−0.379
	(0.245)
R&D p value	0.139
Country fixed effects	Yes
Year fixed effects	Yes
Observations	33
Number of countries	5
Within R^2	0.739
F-statistic	5.10
Model p value	0.001
Joint p value of year effects	0.064

Note: The dependent variable is the logistics performance index. Standard errors are reported in parentheses. The original MEDII is the equally weighted average of standardized internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. The connectivity-only MEDII excludes ICT service exports. The PCA-weighted MEDII is based on the first principal component of the four standardized indicators. Because the indices have different scales, the magnitudes of their coefficients should not be compared directly. Panel C introduces R&D expenditure as an additional control and is based on 33 observations because of two missing R&D values. Given the small sample size and reduced degrees of freedom, the R&D specification should be interpreted as supplementary evidence. $p < 0.10$; $\mathbf{p} < 0.05$; $\boldsymbol{p} < 0.01$.

Table 5 presents a series of robustness analyses designed to assess the sensitivity of the baseline results to alternative index construction methods and the inclusion of an additional innovation-related control variable. Specifically, two alternative versions of the Metaverse-Enabling Digital Infrastructure Index (MEDII) were estimated. The first is a connectivity-only index constructed from standardized measures of internet usage, fixed

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

broadband subscriptions, and mobile cellular subscriptions, excluding ICT service exports. The second is a PCA-weighted index derived from the four original indicators via principal component analysis (PCA).

The PCA results indicate that the first principal component has an eigenvalue of 2.588 and explains 64.69% of the total variance. Internet usage, fixed broadband subscriptions, and mobile cellular subscriptions have positive coefficients on the first principal component, whereas ICT service exports have a negative coefficient. This finding suggests that ICT service exports represent a distinct dimension of digital development related to digital service specialization rather than domestic digital connectivity.

The two-way fixed-effects estimations using these alternative measures produce results that are consistent with the baseline specification. The coefficient of the connectivity-only MEDII is negative but statistically insignificant ($\beta = -0.050$, $p = 0.595$), whereas the PCA-weighted MEDII also yields a negative and statistically insignificant coefficient ($\beta = -0.029$, $p = 0.661$). Furthermore, the joint significance tests confirm that the year fixed effects remain statistically significant in both models ($p = 0.025$ and $p = 0.028$). These findings demonstrate that the absence of a statistically significant relationship between MEDII and logistics performance is robust to alternative index construction methods and is not driven by either the inclusion of ICT service exports or the equal-weighting procedure adopted in the baseline index.

As an additional robustness exercise, R&D expenditure as a percentage of GDP was incorporated into the original two-way fixed-effects model to account for national innovation capacity. Owing to missing observations for the R&D variable, the estimation sample was reduced from 35--33 country-year observations. Although the estimated coefficient of MEDII changed from negative to positive, it remained statistically insignificant ($\beta = 0.135$, $p = 0.468$). Similarly, the coefficient of R&D expenditure was not statistically significant ($\beta = -0.379$, $p = 0.139$). The joint test for year fixed effects was statistically significant only at the 10% level ($F(6,18) = 2.46$, $p = 0.064$).

Taken together, the robustness analyses provide consistent evidence that the main findings are not sensitive to reasonable alternative model specifications. Neither modifying the construction of the digital infrastructure index nor controlling for national R&D intensity produces a statistically significant relationship between the MEDII and logistics performance. While the change in the sign of the MEDII coefficient in the R&D specification suggests some sensitivity to sample size and model specification, the absence of statistical significance across all robustness tests reinforces the conclusion that there is no robust empirical evidence supporting a systematic relationship between metaverse-enabling digital infrastructure and logistics performance in the BRICS economies during the study period.

Table 6. Country- and Year-Based Descriptive Statistics of LPI_Total

Panel A: Country-Based LPI Statistics	N	Mean	Std. Deviation
Brazil	7	3.067	0.154
China	7	3.547	0.126
India	7	3.164	0.193
Russia	7	2.667	0.169
South Africa	7	3.564	0.152
Total	**35**	**3.202**	**0.370**
Panel B: Year-Based LPI Statistics	**N**	**Mean**	**Std. Deviation**
2007	5	2.968	0.462
2010	5	3.176	0.355
2012	5	3.196	0.426
2014	5	3.162	0.333
2016	5	3.341	0.417
2018	5	3.190	0.326
2023	5	3.380	0.342
Total	**35**	**3.202**	**0.370**

Country-level descriptive statistics indicate that there are notable differences in logistics performance among BRICS economies. During the period under examination, South Africa and China presented the highest average LPI values, whereas Russia presented the lowest average level.

In terms of temporal variation, the average LPI value increased from 2.968 in 2007 to 3.380 in 2023. This finding suggests that logistics performance in BRICS economies has generally followed an upward trend over the observed period.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

Table 7. Leave-One-Country-Out Sensitivity Analysis

Excluded country	MEDII coefficient	Standard error	p value
Full sample	−0.074	0.111	0.510
Brazil	−0.074	0.111	0.516
China	0.422	0.281	0.154
India	0.013	0.242	0.958
Russia	−0.068	0.135	0.623
South Africa	−0.084	0.091	0.370

Note: Each specification includes MEDII, exports as a percentage of GDP, log real GDP per capita, country fixed effects, and year fixed effects.

To assess whether the two-way fixed-effects results were disproportionately driven by a particular country, a leave-one-country-out sensitivity analysis was conducted. The main specification was re-estimated five times, each time excluding one BRICS economy. The MEDII coefficient remained statistically insignificant across all specifications, with p values ranging from 0.154--0.958. However, the coefficient ranged from −0.084 when South Africa was excluded to 0.422 when China was excluded. Notably, excluding China changed the sign of the coefficient from negative to positive and substantially increased its magnitude. These findings indicate that the absence of statistical significance is consistent across the alternative samples, but the direction and magnitude of the estimated associations are sensitive to country composition. This sensitivity underscores the need for cautious interpretation given the small number of countries.

5 Conclusion

This study examined whether metaverse-enabling digital infrastructure is associated with logistics performance in the original five BRICS economies. Because consistent country-level data on actual metaverse adoption are not available for the study period, the metaverse-enabling digital infrastructure index (MEDII) was developed by combining standardized measures of internet usage, fixed broadband subscriptions, mobile cellular subscriptions, and ICT service exports. MEDII should therefore be interpreted as an indicator of selected foundational digital conditions that may facilitate metaverse-related logistics applications rather than as a comprehensive measure of national metaverse readiness.

The analysis covered Brazil, China, India, Russia, and South Africa over seven Logistics Performance Index reporting years between 2007 and 2023, producing 35 country-year observations. The descriptive results reveal substantial heterogeneity across the BRICS economies in terms of logistics performance, digital connectivity, digital service capacity, income levels, trade openness, investment, and innovation intensity. The correlation analysis further shows that MEDII is strongly related to internet usage, fixed broadband subscriptions, and mobile connectivity. ICT service exports, however, display a different empirical pattern, suggesting that they capture digital service specialization rather than the same domestic connectivity dimension represented by the other index components.

The regression results do not provide robust evidence of a statistically significant association between MEDII and logistics performance. MEDII is statistically insignificant in the pooled OLS specifications. The country fixed-effects models initially indicate a positive and significant within-country association, but this result does not persist after common year effects are introduced. In the principal two-way fixed-effects models, the MEDII coefficient becomes negative and statistically insignificant, whereas the year effects are jointly significant. This change suggests that the positive association observed in the country fixed effects models may partly reflect common temporal developments affecting the BRICS economies rather than an independent relationship between digital infrastructure and logistics performance.

The robustness analyses support the conclusion regarding statistical insignificance. Excluding ICT service exports and constructing a connectivity-only index does not materially change the findings. Similarly, the PCA-weighted index has no statistically significant association with logistics performance. The supplementary model incorporating R&D expenditure also yields insignificant MEDII and R&D coefficients. Finally, the leave-one-country-out analysis shows that MEDII remains statistically insignificant regardless of which economy is excluded. Nevertheless, the direction and magnitude of the coefficient vary across some specifications, particularly when China is excluded or when a reduced R&D sample is used. The estimated relationship should therefore be interpreted cautiously, as its statistical insignificance is relatively consistent, but its direction and size are sensitive to model specification and country composition.

These findings have important policy implications. Investments in broadband networks, mobile connectivity, cloud services, IoT systems, artificial intelligence, digital twins, and secure digital platforms may remain strategically important for logistics modernization. However, the present results do not demonstrate that improvements in foundational digital infrastructure independently translate into higher national LPI scores. Digital infrastructure is likely to operate as a complementary condition whose contribution depends on physical transport networks, customs administration, institutional quality, workforce capabilities, organizational readiness, logistics-specific technology adoption, and broader investment conditions. Policymakers should therefore integrate digital infrastructure initiatives with transport, customs, innovation, skills, and supply chain modernization policies rather than treating connectivity investment as a sufficient solution by itself.

Several limitations should be acknowledged. First, the sample contains only five countries and 35 observations, limiting the statistical power and precision of the estimated coefficients. Second, the LPI is available only for selected years, has irregular observation intervals, and is partly based on expert perceptions, which may introduce measurement error and restrict the use of conventional dynamic panel techniques. Third, MEDII does not directly measure artificial intelligence, extended reality, digital twins, blockchain, cloud or edge computing, IoT deployment, cybersecurity, or actual metaverse adoption. Fourth, although the models control for income, trade openness, investment, country effects, and year effects, other potentially relevant determinants—such as institutional quality, customs efficiency, transport infrastructure, and governance—could not be incorporated consistently. Finally, the observational design does not fully resolve reverse causality, simultaneity, or residual omitted-variable bias. The estimates should therefore be interpreted as conditional associations rather than causal effects.

Future research could extend the analysis to BRICS+ countries and broader samples of emerging and developed economies, incorporate longer, more regular time series, and use direct indicators of 5G deployment, cloud capacity, IoT adoption, artificial intelligence, digital twins, cybersecurity, and metaverse-related investment. Objective logistics outcomes, including customs clearance times, port throughput, transport costs, shipment reliability, and delivery performance, could also complement the LPI. With richer data, future studies could employ credible instrumental variables, properly aligned lagged specifications, dynamic-panel methods, or quasi-experimental designs to provide stronger evidence on causal mechanisms.

Overall, the study contributes by developing a transparent measure of selected metaverse-enabling digital conditions and evaluating its relationship with logistics performance across the original BRICS economies. The results do not support a robust, independent association between the MEDII and logistics performance after accounting for both country-specific heterogeneity and common year effects. Instead, they emphasize that digital infrastructure should be understood as one element within a broader system of physical, institutional, technological, and organizational capabilities that shape logistics performance.

Acknowledgments

Grammarly was used for language editing and proofreading of this manuscript. Its purpose was solely to improve grammar and language, with the scientific content remaining the author's responsibility.

References

[1] F. K. Tutar, A. Abukalloub, and S. Musayeva, “Economic implications of digitalization and smart agriculture: A comparative study of Poland and Türkiye,” *Current Agronomy*, vol. 54, no. 2, pp. 55–69, Jun. 2025, doi: 10.2478/cag-2025-0006.

[2] F. Kutluay Tutar, S. Canbulut, and N. F. Tutar, “Smart Cities For A Sustainable Life In Local Economic Development,” *International Journal of Disciplines In Economics and Administrative Sciences Studies (IDEAstudies)*, vol. 8, no. 43, pp. 472–495, 2022, doi: 10.29228/ideas.63683.

[3] ABUKALLOUB, A., et al. METAVERSE EKONOMİSİNİN MİKRO VE MAKRO EKONOMİYE ETKİLERİ. Zenodo, 2025, https://doi.org/10.5281/zenodo.15650264.

[4] Tutar, Erdinç, vd. “Türkiye’de Lojistik Sektörünün Gelişmişlik Düzeyinin Seçilmiş AB Ülkeleri (Romanya ve Macaristan) İle Karşılaştırmalı Bir Analizi”. *Karamanoğlu Mehmetbey Üniversitesi Sosyal Ve Ekonomik Araştırmalar Dergisi*, c. 2009, sy 2, Haziran 2009, ss. 190-16, https://izlik.org/JA24AM35UW.

[5] M. Ekici, F. Kutluay Tutar, and N. F. Tutar, “Lojistik Sektöründe Yenilenebilir Enerji, Karbon Emisyon Miktarı ve Ekonomik Büyüme Arasındaki İlişkinin Analizi: Türkiye Örneği,” *Hitit Sosyal Bilimler Dergisi*, vol. 17, no. 2, pp. 259–270, Aug. 2024, doi: 10.17218/hititsbd.1442020.

[6] L.-H. Lee *et al.*, “All One Needs to Know about Metaverse: A Complete Survey on Technological Singularity, Virtual Ecosystem, and Research Agenda,” *Foundations and Trends® in Human–Computer Interaction*, vol. 18, no. 2–3, pp. 100–337, Nov. 2024, doi: 10.1561/1100000095.

[7] S. Dakduk, D. van der Woude, and C. Alarcon Nieto, “Technological Adoption in Emerging Economies: Insights from Latin America and the Caribbean with a Focus on Low-Income Consumers,” 2024. doi: 10.5772/intechopen.112004.

SaNa: Journal of Blockchain, NFTs and Metaverse Technology
Vol 3, Issue 2, August 2025, Pages 215-230
ISSN: 3030-9832 (Media Online)
DOI: https://doi.org/10.58905/sana.v3i2.728

[8] E. Vaz, *Regional Knowledge Economies*. Cham: Springer Nature Switzerland, 2024. doi: 10.1007/978-3-031-76906-1.

[9] I. Jebbor, Z. Benmamoun, and H. Hachimi, “Leveraging Digital Twins and Metaverse Technologies for Sustainable Circular Operations: a Comprehensive Literature Review,” *Circular Economy and Sustainability*, vol. 5, no. 7, pp. 5795–5848, Dec. 2025, doi: 10.1007/s43615-025-00615-2.

[10] Agrawal, Manali, and Prateek Kumar Bansal. "Leveraging Emerging Digital Ecosystem to Attain Long-Term Sustainable Growth." *Metaverse and Sustainability: Business Resilience Towards Sustainable Development Goals*. Cham: Springer Nature Switzerland, 2025. 19-35. https://doi.org/10.1007/978-3-031-89545-6_2

[11] L. Danil, S. Jahroh, R. Syarief, and A. Taryana, “Technological Innovation in Start-Ups on a Pathway to Achieving Sustainable Development Goal (SDG) 8: A Systematic Review,” *Sustainability*, vol. 17, no. 3, p. 1220, Feb. 2025, doi: 10.3390/su17031220.