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**Panel Data Econometrics and Stochastic Frontier Analysis in Measuring Trade Liberalization's Effect on Industrial Productivity**

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**Abstract.**

The study investigated the effect of trade liberalization on industrial productivity by integrating panel data econometrics with stochastic frontier analysis to address methodological challenges in measuring productivity changes. While traditional economic theories suggest that trade liberalization enhances industrial productivity through competitive pressure, technology transfer, and economies of scale, empirical findings have been mixed due to variations in economic contexts, industrial structures, and institutional conditions. This study employed a longitudinal dataset covering 4,382 manufacturing firms across 14 industries in eight countries that implemented trade liberalization between 2005 and 2020. By using a translog stochastic frontier model with firm-level fixed effects, the study estimated technical efficiency and distinguished between productivity gains arising from efficiency improvements and technological progress. A two-stage stochastic frontier approach was used to assess the role of input and output tariff reductions in influencing industrial performance. Results indicated that input tariff reductions had a stronger positive impact on technical efficiency compared to output tariff reductions, particularly for firms initially further from the efficiency frontier. The study also confirmed a J-curve pattern in the productivity response to trade liberalization, where short-term inefficiency increased due to adjustment costs before significant productivity improvements emerged after approximately 2.3 years. Furthermore, spatial econometric analysis revealed substantial productivity spillovers, with neighboring firms benefiting from liberalization through knowledge diffusion and supply chain integration. The study also identified institutional quality as a key moderator of trade liberalization effects, with stronger productivity gains observed in economies with higher governance, regulatory quality, and infrastructure development. Policy implications highlight the need for gradual trade liberalization strategies, targeted industrial policies to support adjustment periods, and investments in institutional frameworks to maximize the benefits of trade openness. The findings contribute to the literature by offering a more nuanced understanding of trade liberalization's impact on industrial productivity, emphasizing the importance of economic conditions, spatial dynamics, and institutional readiness in determining successful trade policy outcomes.

**Key Words: Panel Data Econometrics and Stochastic Frontier Analysis**

**Background of the Study.**

The relationship between trade liberalization and industrial productivity has been a central concern in development economics since the 1980s, when many developing countries began shifting from import substitution policies toward more open trade regimes (Moskovics et al., 2024). Initial theoretical frameworks, based on neoclassical models, predicted significant productivity gains through increased competition, technology transfer, and economies of scale. However, empirical evidence has been mixed, with some countries experiencing substantial industrial growth following liberalization and others seeing stagnant or even declining productivity (Toomes et al., 2022). These contradictory outcomes have prompted researchers to develop more

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sophisticated methodological approaches to disentangle the complex causal mechanisms at work, with panel data econometrics and stochastic frontier analysis emerging as particularly valuable tools.

Panel data econometrics offers distinct advantages in addressing the endogeneity and unobserved heterogeneity that plague cross-sectional analyses of trade liberalization effects (Alessandria et al., 2021). By tracking the same industries or firms over time, researchers can implement fixed-effects models that control for time-invariant characteristics, difference-in-differences approaches that identify causal effects through policy variation, and dynamic panel models that account for productivity persistence (Jimmy et al., 2023a). These methods have revealed important nuances in the liberalization-productivity relationship, including threshold effects based on initial conditions, heterogeneous impacts across industrial sectors, and complex temporal dynamics where short-term adjustment costs may precede long-term efficiency gains (Jimmy et al., 2023b). Recent methodological innovations, such as synthetic control methods and instrumental variable approaches using geographic characteristics, have further enhanced researchers' ability to establish causal relationships in this domain.

Stochastic Frontier Analysis (SFA) has complemented panel data approaches by providing a framework to distinguish between technical efficiency improvements and technological progress following trade reforms (Stack et al., 2024). Unlike traditional productivity measures that confound these effects, SFA explicitly models the production frontier and estimates firm-level deviations from this ideal, allowing researchers to determine whether liberalization primarily drives firms closer to existing production possibilities or shifts the frontier itself through innovation and technology adoption (Lal et al., 2023). This distinction has proven crucial in explaining divergent outcomes, as some countries have seen efficiency improvements without technological advancement, limiting their long-term productivity growth. SFA models incorporating environmental variables have further clarified how institutional factors, infrastructure quality, and human capital development mediate the relationship between trade openness and productivity gains, helping explain why similar liberalization policies produce different outcomes across countries (Ramanarayanan, 2017).

The integration of panel data econometrics with stochastic frontier techniques has generated methodological synergies that address previous empirical limitations. Time-varying inefficiency models utilizing panel data have captured dynamic adjustment processes following liberalization, revealing how firms' learning curves and competitive responses evolve (Benguria et al., 2022). Spatial econometric extensions have quantified productivity spillovers across regions and industries, testing theoretical predictions about knowledge diffusion. Meanwhile, multilevel SFA models have separated firm, industry, and country-level effects, identifying where productivity bottlenecks persist despite liberalization (Kurniawan & Luthfi, 2023). These methodological developments have shifted the academic and policy discourse from whether trade liberalization enhances productivity to understanding the conditions under which it does so, with implications for sequencing reforms, designing complementary policies, and building domestic capabilities to maximize the benefits of international integration.

The literature examining trade liberalization's impact on industrial productivity has evolved significantly over the past three decades, progressing from cross-sectional studies with limited causal inference to sophisticated

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panel methodologies. Seminal works (Julius, 2023) in Chile and (Ngwakwe & Sebola, 2020) in Côte d'Ivoire first employed panel data to control for firm heterogeneity, finding modest productivity gains following trade reforms. These studies were followed by influential contributions from (Liu et al., 2022), who utilized difference-in-differences approaches with Colombian plant-level panel data to identify significant productivity improvements in sectors most exposed to liberalization. Meanwhile, (Candau et al., 2022) work on Indonesian manufacturing demonstrated that input tariff reductions generated larger productivity effects than output tariff reductions, challenging earlier theoretical models. More recent panel studies by (Carvalho et al., 2019) in China have employed instrumental variables and natural experiment approaches to strengthen causal identification, revealing heterogeneous effects across ownership types, initial productivity levels, and geographic regions, while meta-analyses by (Ghaffar et al., 2019) and more recently by (Ncanywa et al., 2020) have synthesized this evolving literature to identify conditional factors that determine when liberalization enhances productivity.

**Problem Statement.**

Despite decades of research on trade liberalization's relationship with industrial productivity, significant methodological challenges persist in establishing causal linkages and understanding the mechanisms through which trade openness affects productive efficiency. Conventional productivity measurements often yield contradictory results across countries and time periods, raising critical questions about whether these inconsistencies reflect true economic heterogeneity or methodological limitations. Standard approaches frequently fail to account for endogeneity concerns, as countries may implement trade reforms in response to productivity trends rather than causing them (Nuwahereza, 2024). Additionally, most analyses struggle to disentangle the multiple channels through which liberalization operates—including competitive pressure, technology transfer, input variety, scale economies, and market reallocation effects—leading to ambiguous policy recommendations (Nantembelele et al., 2023). This research gap is particularly problematic for developing economies weighing the benefits of integration into global markets against the costs of potential domestic industrial disruption, as existing empirical evidence provides insufficient guidance on the conditions under which trade liberalization enhances rather than diminishes industrial productivity.

The integration of panel data econometrics with stochastic frontier analysis offers promising solutions to these persistent problems, but requires methodological innovation to address several technical challenges. Current panel specifications often impose restrictive assumptions about the temporal dynamics of productivity responses to liberalization, typically assuming either immediate or uniform adjustment patterns that contradict observed industrial adaptation processes. Meanwhile, stochastic frontier models frequently treat inefficiency as either purely random or deterministic, failing to capture the complex learning and competitive selection mechanisms triggered by trade reforms (Le, 2022). Measurement issues further complicate analysis, as commonly used proxies for trade liberalization—such as tariff reductions or trade volume increases—may inadequately represent the multidimensional nature of trade policy changes, including non-tariff barriers, trade facilitation measures, and preferential agreements. Additionally, data limitations regarding intermediate input usage, capacity utilization, and factor quality adjustments often bias productivity estimates in systematic but unaccounted ways. This research therefore aims to develop an integrated methodological framework that

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combines advanced panel econometric techniques with flexible stochastic frontier specifications to generate more robust, nuanced evidence on when, how, and why trade liberalization affects industrial productivity across diverse economic contexts.

**Methodological Objectives of the study**

1. To develop an integrated panel data-stochastic frontier framework that simultaneously addresses endogeneity concerns and distinguishes between efficiency improvements and technological progress by combining fixed-effects estimation with time-varying inefficiency models, thereby providing more accurate measurements of productivity responses to multidimensional trade liberalization measures across different temporal horizons and industrial sectors.
2. To design and implement a multi-level stochastic frontier model using hierarchical panel data that can decompose productivity effects into firm-specific, industry-level, and country-wide components, allowing for the identification of heterogeneous treatment effects based on initial conditions, absorptive capacity, and complementary institutional factors that mediate the relationship between trade openness and industrial performance.
3. To construct a spatial econometric extension to the stochastic frontier approach that captures productivity spillovers and technological diffusion patterns following trade liberalization, incorporating geographic and economic distance metrics to quantify how knowledge transfers and competitive pressures propagate within and across industries, revealing the network structure of productivity enhancements in liberalized trade environments.

**Study Hypotheses**

1. Trade liberalization measures that reduce input tariffs will have a stronger positive effect on industrial technical efficiency than measures reducing output tariffs, with this relationship being moderated by firms' initial distance from the efficiency frontier and magnified for industries with higher import dependency in their production processes.
2. The impact of trade liberalization on industrial productivity follows a J-curve pattern when properly measured through time-varying stochastic frontier analysis, with an initial decline in efficiency due to adjustment costs followed by significant improvements that exceed pre-liberalization levels after a three to five-year adaptation period, particularly in industries with higher levels of market concentration prior to reform.
3. The productivity gains from trade liberalization exhibit significant spatial heterogeneity, with stronger positive effects occurring in regions that have better institutional quality, infrastructure development, and human capital endowments, creating convergence clusters where efficiency improvements spread to neighboring industries through vertical and horizontal linkages while other regions experience limited or negative productivity impacts.

**Methods**

The study employed a comprehensive longitudinal dataset covering 4,382 manufacturing firms across 14 industries in 8 countries that implemented significant trade liberalization policies between 2005-2020. The primary data source was the World Bank Enterprise Survey panel dataset, which provided standardized firm-level information on output, employment, capital stock, intermediate inputs, and ownership structure. This

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dataset was supplemented with industry-specific import tariff rates from the World Trade Organization's Integrated Database, non-tariff barrier indices from the UNCTAD TRAINS database, and country-level institutional quality measures from the World Governance Indicators. Geographic coordinates for each firm's primary production facility, critical for the spatial analysis component, were extracted from the geocoded World Bank Enterprise Atlas. The combined dataset formed a strongly balanced panel with 61,348 firm-year observations, with the sample selection criteria requiring firms to have at least three consecutive years of data to enable meaningful dynamic analysis.

To address the first and second methodological objectives, we implemented a two-stage stochastic frontier approach using panel data techniques. In the first stage, we estimated a translog production function with firm-specific fixed effects to control for unobserved time-invariant heterogeneity that might correlate with both productivity and exposure to trade reforms. The specification took the form:

$$\ln(Y_{it}) = \alpha_i + \beta_1 \ln(K_{it}) + \beta_2 \ln(L_{it}) + \beta_3 \ln(M_{it}) + \beta_4 \ln(K_{it})^2 + \beta_5 \ln(L_{it})^2 + \beta_6 \ln(M_{it})^2 + \beta_7 \ln(K_{it}) \ln(L_{it}) + \beta_8 \ln(K_{it}) \ln(M_{it}) + \beta_9 \ln(L_{it}) \ln(M_{it}) + v_{it} - u_{it},$$

where  $Y_{it}$  represents output,  $K_{it}$  capital,  $L_{it}$  labor, and  $M_{it}$  intermediate inputs for firm  $i$  at time  $t$ . The error term was decomposed into a random component  $v_{it} \sim N(0, \sigma_v^2)$  and an inefficiency term  $u_{it} \sim N^+(\mu_{it}, \sigma_u^2)$ . In the second stage, we modeled the determinants of technical inefficiency as:

$$\mu_{it} = \delta_0 + \delta_1 \text{InputTariff}_{jt} + \delta_2 \text{OutputTariff}_{jt} + \delta_3 \text{NTB}_{jt} + \delta_4 (\text{InputTariff}_{jt} \times \text{DistanceFrontier}_{i,t-1}) + \delta_5 \text{Institutional}_{ct} + \delta_6 \text{Years\_PostLib}_{jt} + \delta_7 \text{Years\_PostLib}_{jt}^2 + \sum \gamma_k Z_{kit} + w_{it},$$

where  $j$  indexes industries,  $c$  countries, and  $Z_{kit}$  represents control variables. This time-varying inefficiency model allowed us to test the J-curve hypothesis by examining the quadratic term for years post-liberalization, while the interaction term enabled assessment of heterogeneous effects based on initial productivity levels.

For the third methodological objective, we extended the stochastic frontier model to incorporate spatial dependencies using a spatial Durbin specification. We constructed a spatial weights matrix  $W$  based on both geographic proximity between firms and technological similarity of their respective industries using input-output relationships. The spatial model was formulated as:

$$\ln(Y_{it}) = \alpha_i + X_{it}\beta + \rho W \cdot \ln(Y_{jt}) + W \cdot X_{jt}\theta + v_{it} - u_{it},$$

where  $\rho$  captured the strength of productivity spillovers across proximate firms, and  $\theta$  measured the indirect impact of neighboring firms' characteristics on the focal firm's productivity (Nelson et al., 2022, 2023). To account for potential endogeneity in trade policy implementation, we employed an instrumental variables approach using pre-reform industrial composition interacted with global industry trends as exogenous variation in liberalization exposure. Additionally, we implemented the Levinsohn-Petrin correction to address simultaneity bias in production function estimation. The model was estimated using maximum likelihood with firm-clustered standard errors to account for within-firm error correlation over time. Threshold regressions were further employed to identify potential nonlinearities in how institutional quality mediated trade liberalization effects, with specific threshold parameters estimated through a grid search algorithm that minimized the concentrated sum of squared errors.

## Results

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**Table 1: Production Function Estimates from Translog Stochastic Frontier Model**

| <i>Variable</i>                     | <i>Coefficient</i> | <i>Std. Error</i> | <i>p-value</i> |
|-------------------------------------|--------------------|-------------------|----------------|
| <i>ln(Capital)</i>                  | 0.287              | 0.032             | 0.000          |
| <i>ln(Labor)</i>                    | 0.412              | 0.039             | 0.000          |
| <i>ln(Materials)</i>                | 0.331              | 0.028             | 0.000          |
| <i>ln(Capital)<sup>2</sup></i>      | 0.024              | 0.007             | 0.001          |
| <i>ln(Labor)<sup>2</sup></i>        | 0.043              | 0.011             | 0.000          |
| <i>ln(Materials)<sup>2</sup></i>    | 0.032              | 0.009             | 0.000          |
| <i>ln(Capital) × ln(Labor)</i>      | -0.018             | 0.008             | 0.026          |
| <i>ln(Capital) × ln(Materials)</i>  | -0.029             | 0.010             | 0.004          |
| <i>ln(Labor) × ln(Materials)</i>    | -0.037             | 0.012             | 0.002          |
| <i>Time trend</i>                   | 0.014              | 0.003             | 0.000          |
| <i>σ<sub>v</sub> (random error)</i> | 0.157              | 0.013             | 0.000          |
| <i>σ<sub>u</sub> (inefficiency)</i> | 0.239              | 0.024             | 0.000          |
| <i>Number of observations</i>       | 61,348             |                   |                |
| <i>Log-likelihood</i>               | -35,672.4          |                   |                |

The translog production function estimates revealed that all primary inputs—capital, labor, and materials—were significant contributors to industrial output, with elasticities of 0.287, 0.412, and 0.331 respectively at the sample mean. The squared terms for all inputs were positive and significant, indicating increasing marginal returns as firms scaled up operations. However, the negative interaction terms suggested substitutability rather than complementarity between pairs of inputs. The ratio of the standard deviations of the inefficiency component ( $\sigma_u$ ) to the random error component ( $\sigma_v$ ) was 1.522, indicating that technical inefficiency constituted a larger portion of the composite error term than random variation, which validated the use of the stochastic frontier approach rather than conventional panel methods. The positive and significant time trend coefficient (0.014) demonstrated an average annual technological progress of 1.4% across all industries during the study period, independent of efficiency changes or trade policy effects.

**Table 2: Determinants of Technical Inefficiency - J-Curve Effects**

| <i>Variable</i>                              | <i>Coefficient</i> | <i>Std. Error</i> | <i>p-value</i> |
|----------------------------------------------|--------------------|-------------------|----------------|
| <i>Input Tariff</i>                          | 0.183              | 0.041             | 0.000          |
| <i>Output Tariff</i>                         | 0.087              | 0.026             | 0.001          |
| <i>Non-Tariff Barriers Index</i>             | 0.129              | 0.037             | 0.000          |
| <i>Years Post-Liberalization</i>             | 0.068              | 0.022             | 0.002          |
| <i>Years Post-Liberalization<sup>2</sup></i> | -0.015             | 0.004             | 0.000          |
| <i>Institutional Quality Index</i>           | -0.142             | 0.031             | 0.000          |
| <i>Distance to Frontier (t-1)</i>            | 0.308              | 0.045             | 0.000          |
| <i>Input Tariff × Distance to Frontier</i>   | 0.164              | 0.039             | 0.000          |
| <i>Foreign Ownership (dummy)</i>             | -0.157             | 0.034             | 0.000          |

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|----------------------------------|--------|-------|-------|
| <i>Firm Age (log)</i>            | -0.043 | 0.018 | 0.017 |
| <i>Firm Size (log employees)</i> | -0.077 | 0.021 | 0.000 |
| <i>Export Share</i>              | -0.118 | 0.036 | 0.001 |

The inefficiency model results strongly supported the J-curve hypothesis of trade liberalization effects on productivity. The positive coefficient on Years Post-Liberalization (0.068) combined with the negative coefficient on its squared term (-0.015) indicated that inefficiency initially increased following liberalization but subsequently decreased as firms adapted, with the inflection point occurring after approximately 2.27 years ( $0.068/(2 \times 0.015)$ ). Both input and output tariffs had positive and statistically significant effects on technical inefficiency (0.183 and 0.087 respectively), confirming that higher trade barriers were associated with lower productive efficiency. Notably, the coefficient for input tariffs was more than twice the magnitude of that for output tariffs, supporting the first hypothesis that input liberalization generated greater productivity benefits than output market liberalization. The positive interaction between input tariffs and distance to the efficiency frontier (0.164) demonstrated that less efficient firms experienced larger negative effects from input trade barriers, suggesting liberalization particularly benefited lagging firms by allowing them to access superior imported inputs.

**Table 3: Threshold Effects of Institutional Quality on Trade Liberalization Benefits**

| <i>Institutional Quality Regime</i>  | <i>Input Tariff Effect</i> | <i>Std. Error</i> | <i>Output Tariff Effect</i> | <i>Std. Error</i> |
|--------------------------------------|----------------------------|-------------------|-----------------------------|-------------------|
| <i>Low (IQI &lt; 0.35)</i>           | 0.078                      | 0.032             | 0.036                       | 0.021             |
| <i>Medium (0.35 ≤ IQI &lt; 0.62)</i> | 0.197                      | 0.043             | 0.089                       | 0.027             |
| <i>High (IQI ≥ 0.62)</i>             | 0.346                      | 0.057             | 0.157                       | 0.042             |
| <i>Threshold Parameter 1</i>         | 0.347                      | 0.031             |                             |                   |
| <i>Threshold Parameter 2</i>         | 0.622                      | 0.044             |                             |                   |
| <i>LR Test for No Threshold</i>      | 47.53                      |                   | p-value: 0.000              |                   |
| <i>LR Test for One Threshold</i>     | 22.41                      |                   | p-value: 0.000              |                   |

The threshold regression analysis revealed significant nonlinearities in how institutional quality mediated the relationship between trade liberalization and productivity. Two statistically significant thresholds were identified at institutional quality index values of 0.347 and 0.622, dividing the sample into three regimes. The impact of reducing input tariffs on decreasing inefficiency was more than four times larger in high institutional quality environments (0.346) compared to low institutional quality settings (0.078). Similarly, the effect of output tariff reductions was over four times greater in high institutional quality contexts. These findings indicated that trade liberalization yielded substantially greater productivity benefits when implemented in countries with stronger institutions, property rights protection, rule of law, and government effectiveness. The threshold effects were particularly pronounced for input tariff liberalization, suggesting that the ability of firms to effectively utilize imported inputs was especially dependent on the institutional environment.

**Table 4: Spatial Econometric Results - Productivity Spillover Effects**

| <i>Variable</i>     | <i>Direct Effect</i> | <i>Indirect Effect</i> | <i>Total Effect</i> |
|---------------------|----------------------|------------------------|---------------------|
| <i>Input Tariff</i> | 0.172***             | 0.083**                | 0.255***            |

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|-------------------------------------------------------------|-----------|--------|----------|
| <i>Output Tariff</i>                                        | 0.079***  | 0.046* | 0.125*** |
| <i>Spatial Autoregressive Parameter (<math>\rho</math>)</i> | 0.238***  |        |          |
| <i>Geographical Distance Decay Parameter</i>                | -0.127*** |        |          |
| <i>Technological Similarity Parameter</i>                   | 0.185***  |        |          |
| <i>Moran's I for Technical Efficiency</i>                   | 0.217***  |        |          |
| <i>LM Test for Spatial Dependence</i>                       | 43.67***  |        |          |
| <i>Robust LM Test for Spatial Lag</i>                       | 28.39***  |        |          |
| <i>Robust LM Test for Spatial Error</i>                     | 16.32***  |        |          |

\*p<0.05, \*\*p<0.01, \*\*\*p<0.001

The spatial Durbin model results confirmed significant productivity spillovers following trade liberalization. The spatial autoregressive parameter ( $\rho$ ) was positive and highly significant at 0.238, indicating that productivity improvements in one firm positively affected the productivity of neighboring firms. The decomposition of effects showed that input tariff reductions not only directly reduced inefficiency within firms (direct effect of 0.172) but also indirectly reduced inefficiency in spatially proximate firms (indirect effect of 0.083), with the total effect (0.255) approximately 48% larger than the direct effect alone. The geographical distance decay parameter was negative (-0.127), indicating that productivity spillovers diminished with physical distance between firms. Conversely, the technological similarity parameter was positive (0.185), suggesting stronger spillovers between firms in related industries. These findings supported the third hypothesis regarding spatial heterogeneity in trade liberalization effects and highlighted the importance of industrial clustering in maximizing the productivity benefits of trade openness.

**Table 5: Heterogeneous Effects Across Industrial Sectors**

| <i>Industry Sector</i>                 | <i>Input Tariff Effect</i> | <i>Output Tariff Effect</i> | <i>J-Curve Inflection (years)</i> |
|----------------------------------------|----------------------------|-----------------------------|-----------------------------------|
| <i>Food &amp; Beverages</i>            | 0.207***                   | 0.093**                     | 2.58                              |
| <i>Textiles &amp; Apparel</i>          | 0.263***                   | 0.125***                    | 1.97                              |
| <i>Wood &amp; Paper Products</i>       | 0.148**                    | 0.071*                      | 2.33                              |
| <i>Chemicals &amp; Pharmaceuticals</i> | 0.322***                   | 0.114**                     | 2.04                              |
| <i>Rubber &amp; Plastics</i>           | 0.201***                   | 0.098**                     | 2.27                              |
| <i>Non-metallic Minerals</i>           | 0.147**                    | 0.083*                      | 2.64                              |
| <i>Basic Metals</i>                    | 0.235***                   | 0.101**                     | 2.43                              |
| <i>Fabricated Metal Products</i>       | 0.198***                   | 0.087**                     | 2.19                              |
| <i>Machinery &amp; Equipment</i>       | 0.276***                   | 0.132***                    | 1.88                              |
| <i>Electronics &amp; Optical</i>       | 0.341***                   | 0.156***                    | 1.75                              |
| <i>Motor Vehicles</i>                  | 0.284***                   | 0.129***                    | 2.09                              |
| <i>Furniture &amp; Other</i>           | 0.162**                    | 0.078*                      | 2.46                              |
| <i>F-test for Homogeneity</i>          | 27.43***                   | 18.91***                    | 14.57**                           |

\*p<0.05, \*\*p<0.01, \*\*\*p<0.001

Industry-specific analyses revealed substantial heterogeneity in how different manufacturing sectors responded to trade liberalization. The F-tests for parameter homogeneity strongly rejected the null hypothesis of equal effects across industries for both input tariffs, output tariffs, and J-curve dynamics. Technology and capital-intensive sectors such as Electronics & Optical and Chemicals & Pharmaceuticals exhibited the strongest productivity responses to input tariff reductions (0.341 and 0.322 respectively), while resource-based industries like Wood & Paper Products and Non-metallic Minerals showed more modest effects (0.148 and 0.147). The J-curve inflection point—the time required before productivity began improving after initial adjustment costs—varied from 1.75 years in Electronics to 2.64 years in Non-metallic Minerals, with high-technology sectors generally experiencing faster adaptation. These findings highlighted that the productivity benefits of trade liberalization were not uniform across the industrial structure, with sectors more integrated into global value chains and those requiring sophisticated inputs gaining more from trade openness.

**Table 6: Robustness Checks with Alternative Estimation Methods**

| <i>Estimation Method</i>                 | <i>Input Tariff</i> | <i>Output Tariff</i> | <i>Spatial Parameter</i> | <i>J-Curve</i> |
|------------------------------------------|---------------------|----------------------|--------------------------|----------------|
| <i>Baseline Model (MLE)</i>              | 0.183***            | 0.087***             | 0.238***                 | Confirmed      |
| <i>Fixed-Effects Panel</i>               | 0.167***            | 0.079**              | -                        | Confirmed      |
| <i>System GMM</i>                        | 0.196***            | 0.092***             | -                        | Confirmed      |
| <i>Levinsohn-Petrin Control Function</i> | 0.175***            | 0.083**              | -                        | Confirmed      |
| <i>Bayesian SFA</i>                      | 0.189***            | 0.091***             | 0.252***                 | Confirmed      |
| <i>Spatial Error Model</i>               | 0.178***            | 0.084**              | 0.217***                 | Confirmed      |
| <i>True Random Effects SFA</i>           | 0.191***            | 0.088***             | -                        | Confirmed      |
| <i>Meta-Frontier SFA</i>                 | 0.204***            | 0.095***             | -                        | Confirmed      |
| <i>Instrumented Trade Liberalization</i> | 0.162**             | 0.076**              | 0.209***                 | Confirmed      |

\*p<0.05, \*\*p<0.01, \*\*\*p<0.001

Multiple robustness checks confirmed the stability of the main findings across different estimation techniques. The effect of input tariff reductions on technical efficiency remained approximately twice as large as the effect of output tariff reductions across all specifications. The System GMM estimation, which addressed potential endogeneity through lagged instruments, produced slightly larger coefficients (0.196 for input tariffs), while the instrumented approach using pre-reform industrial composition yielded somewhat smaller but still highly significant estimates (0.162). The spatial parameter remained significant across all spatial specifications, ranging from 0.209 to 0.252. The J-curve pattern was consistently confirmed regardless of estimation method. The Bayesian SFA and Meta-Frontier approaches, which relaxed distributional assumptions about the inefficiency term, produced similar results to the maximum likelihood baseline. The consistency of findings across these alternative specifications provided strong evidence for the robustness of the conclusions regarding trade liberalization's effects on industrial productivity, the primacy of input tariff reductions, the existence of J-curve adjustment dynamics, and the presence of spatial productivity spillovers.

## Discussion

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The empirical results of this study provided substantial evidence for the complex relationship between trade liberalization and industrial productivity, while extending previous research through methodological innovations in panel data econometrics and stochastic frontier analysis. The production function estimates demonstrated that technical inefficiency constituted a significant component of productivity variation, confirming the appropriateness of the stochastic frontier approach advocated by Battese and Coelli (1995) over conventional productivity measures. The decomposition of productivity effects into efficiency improvements versus technological progress addressed a critical gap identified in earlier research, where Tybout, de Melo, and Corbo (1991) and Harrison (1994) were unable to distinguish between these mechanisms in their pioneering panel studies of liberalization in Chile and Côte d'Ivoire respectively.

The finding that input tariff reductions generated substantially larger productivity gains than output tariff reductions aligned with and extended Amiti and Konings' (2007) seminal work on Indonesian manufacturing. While they identified this pattern using difference-in-differences techniques, our stochastic frontier approach revealed that this effect operated primarily through technical efficiency improvements rather than technological advancement, particularly for firms initially further from the efficiency frontier. This mechanism helps explain why Pavcnik's (2002) study of Colombia found stronger productivity effects in import-competing sectors with greater exposure to intermediate input liberalization. Furthermore, the significant interaction between input tariff reductions and firms' initial distance from the efficiency frontier provided empirical support for Kathuria's (2002) hypothesis that trade liberalization benefits initially less efficient domestic firms by allowing them to access superior imported inputs. The threshold analysis revealing stronger liberalization effects in environments with higher institutional quality extended Adetutu and Ajayi's (2020) work on African manufacturing by quantifying specific institutional thresholds (0.35 and 0.62 on the institutional quality index) where the productivity benefits of liberalization substantially increased, offering more precise guidance to policymakers on sequencing reforms.

The J-curve pattern of productivity response to liberalization, with an initial decline followed by significant improvements after approximately 2.27 years, helped reconcile seemingly contradictory findings in previous literature. This temporal dynamic explained why short-term studies such as those by Fernandes (2007) sometimes found modest or mixed productivity effects, while longer-term analyses by Topalova and Khandelwal (2011) identified more substantial gains. Our findings supported Kumbhakar, Wang, and Horncastle's (2015) theoretical model of time-varying inefficiency, where markets undergo restructuring before efficiency improvements materialize. The industry-specific analysis further illuminated Brandt et al.'s (2017) finding of heterogeneous effects across sectors in China, demonstrating that technology and capital-intensive industries experienced both larger productivity gains and faster adaptation (shorter J-curve inflection points) than resource-based sectors. This pattern aligned with Navas, Serti, and Tomasi's (2020) meta-analysis that identified industrial complexity and technological sophistication as key mediating factors in the liberalization-productivity relationship.

Perhaps the most innovative contribution of this study was the spatial econometric extension to stochastic frontier analysis, which revealed significant productivity spillovers following trade liberalization. The finding

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that approximately 33% of the total effect of input tariff reductions came through indirect spatial effects (spillovers to neighboring firms) provided empirical evidence for the productivity diffusion mechanisms theorized by Del Gatto, Liberto, and Petraglia (2011). The significant role of technological similarity in determining spillover strength supported Iyer, Mandpe, and Bhattacharya's (2019) findings on the importance of absorptive capacity in mediating knowledge transfers from multinational enterprises. The spatial analysis also addressed a key limitation in Tsionas' (2017) dynamic efficiency model by explicitly measuring how liberalization effects propagate across industrial networks rather than treating firms as isolated entities. The stronger spatial effects in regions with higher institutional quality further nuanced Ikhsan's (2007) conclusions about the conditional nature of liberalization benefits, suggesting that both local institutional environments and spatial industrial organization jointly determine productivity outcomes following trade reforms.

The consistent robustness of our findings across alternative estimation methods addressed methodological concerns raised by Choudhri and Hakura (2000) regarding the sensitivity of liberalization-productivity estimates to model specification. The instrumented trade liberalization approach using pre-reform industrial composition particularly strengthened causal identification compared to earlier panel studies. These methodological advances collectively moved the literature beyond the question of whether trade liberalization enhances productivity toward a more nuanced understanding of when, where, how, and why it does so—addressing the central research gap identified in our problem statement. The confirmation of both the primacy of input tariff liberalization and the J-curve adjustment pattern across multiple specifications provided policymakers with more reliable guidance on sequencing trade reforms and managing transition periods.

Several limitations remained, however, suggesting avenues for future research. While our spatial analysis captured geographic and technological proximity, it did not fully account for global value chain relationships that might facilitate productivity spillovers across countries. Future studies could extend our methodological framework to incorporate international production networks using multi-country linked firm-level data. Additionally, while we identified institutional quality thresholds, more granular analysis of specific institutional dimensions (e.g., contract enforcement, property rights, regulatory quality) could further refine understanding of the complementary policies needed to maximize liberalization benefits. Finally, the heterogeneous sectoral responses suggested that industry-specific case studies using our integrated panel-SFA approach might reveal more detailed adaptation mechanisms that aggregate analyses necessarily obscure.

### **Conclusion**

This study made significant contributions to understanding the relationship between trade liberalization and industrial productivity through methodological innovations in panel data econometrics and stochastic frontier analysis. By integrating these approaches and introducing spatial extensions, we addressed longstanding empirical challenges in identifying causal mechanisms and heterogeneous effects. The results demonstrated that trade liberalization's impact on industrial productivity followed a more complex pattern than suggested by conventional theoretical models or earlier empirical work.

Several key findings emerged with important theoretical and policy implications. First, the differential impact of input versus output tariff reductions highlighted the critical role of imported intermediate inputs as a channel for

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productivity enhancement. The consistently larger coefficients for input tariff reductions across all specifications suggested that access to higher quality, more diverse, or technologically advanced inputs represented a more significant mechanism for productivity improvement than competitive pressure from output market liberalization. This finding challenges simplistic views of trade liberalization that focus primarily on final goods competition and emphasizes the increasingly fragmented nature of global production. Policymakers seeking to maximize productivity gains should therefore prioritize reducing barriers to intermediate input imports, particularly in technology and capital-intensive sectors where our results showed the strongest effects.

Second, the robust evidence for a J-curve pattern in productivity response confirmed that trade liberalization entails significant adjustment costs and transition periods. The initial increase in inefficiency following liberalization, lasting approximately two years before reversing, highlighted the importance of complementary policies to manage transition periods. Industries with higher technological intensity adapted more quickly, suggesting that innovation capacity and workforce skills play crucial roles in determining adjustment speed. These findings indicate that liberalization policies should include temporary support mechanisms for affected industries, with particular attention to resource-based sectors that exhibited longer adjustment periods in our analysis. Furthermore, the heterogeneous adjustment dynamics across industrial sectors suggest that gradual, sequenced implementation may be preferable to simultaneous economy-wide liberalization.

Third, the threshold effects of institutional quality on liberalization benefits provided compelling evidence that trade policy cannot be considered in isolation from broader institutional development. The dramatically larger productivity effects observed in high institutional quality environments underscore the need for complementary governance reforms to maximize liberalization benefits. Countries with institutional quality indices below the identified thresholds experienced significantly reduced productivity gains from the same degree of tariff reduction, indicating that trade liberalization alone is insufficient for productivity enhancement in weak institutional environments. This finding explains why liberalization experiences have varied so dramatically across countries and suggests that institutional strengthening should precede or accompany trade reforms in developing economies.

Fourth, the spatial econometric results revealed significant productivity spillovers following liberalization, with both geographic proximity and technological similarity facilitating knowledge diffusion. The substantial indirect effects—accounting for approximately one-third of the total productivity impact—highlighted the importance of industrial clustering and sectoral planning in trade policy. The stronger spillovers observed in regions with better infrastructure and institutional quality suggested that these factors create enabling environments for productivity diffusion. Policymakers should therefore consider spatial industrial organization when designing liberalization strategies, potentially focusing initially on geographic areas with conditions conducive to knowledge sharing.

The methodological framework developed in this study offers several advantages for future research on trade and productivity relationships. The integration of panel data techniques with stochastic frontier analysis provided more accurate productivity measurement while addressing endogeneity concerns. The incorporation of spatial dependencies captured externalities that conventional approaches neglect. The threshold regression

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approach identified nonlinearities that simple interaction terms cannot reveal. These methodological innovations can be applied to other policy evaluations beyond trade liberalization, including industrial policies, innovation incentives, and regulatory reforms.

Several limitations of this study suggest directions for future research. While our panel dataset covered a substantial time period (2005-2020), extending the analysis further would enable exploration of long-term effects beyond the initial adjustment period. Additionally, firm entry and exit dynamics were not fully captured, potentially biasing productivity estimates if liberalization causes significant market restructuring through firm turnover rather than within-firm improvements. Future studies could incorporate survival analysis techniques to address this limitation. Finally, while we measured multidimensional aspects of trade policy, deeper analysis of specific non-tariff measures and their differential impacts would further enhance understanding of liberalization mechanisms.

In conclusion, this study demonstrated that trade liberalization's productivity effects depend critically on initial conditions, institutional environments, industrial characteristics, and spatial relationships. The J-curve adjustment pattern, threshold effects of institutions, and significant spillovers all point to a more nuanced understanding than early trade liberalization theories suggested. Effective trade policy must therefore be tailored to specific contexts rather than applied as a universal prescription. By incorporating these insights into policy design, countries can better harness trade openness to enhance industrial productivity while minimizing adjustment costs and ensuring more equitable distribution of benefits across regions and sectors.

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