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# The Role of Human Capital, Innovation, and $CO_2$ Intensity in International Trade in Developed Countries

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## ABSTRACT
With an emphasis on the functions of human capital innovation and $CO_2$ intensity, the current study empirically examines the factors that influence international trade in a panel of developed economies. Innovation, industrialization, and the human capital index are strong and important factors that support international trade in developed nations, according to the analysis, which uses Pooled Mean Group (PMG) regression. Tariffs and interest rates, on the other hand, have been shown to drastically lower trade activity. Strong long-term equilibrium relationships are indicated by significant error correction terms (ECTs), which further support the model's robustness. Instead of employing broad tariffs, policymakers should invest in innovation, $CO_2$ mitigation, and targeted subsidies to increase trade. It's also critical to reduce trade barriers and pay attention to how interest rates impact export competitiveness.

**Keywords:** International Trade, Human Capital, Innovation, $CO_2$ Intensity, PMG Regression, Developed Economies, Trade Policy.

## Introduction
Human capital—encompassing the education, skills, and innovative capacity of a nation's workforce—has emerged as a central determinant in shaping international trade patterns and economic performance. For instance, research on global value chains (GVCs) finds that countries with higher levels of skilled labor achieve greater domestic value-added in exports, underscoring the importance of education and training in capturing the benefits of global production networks (wang and Thangavelu, 2021)
The current research posits that in developed economies**,** human capitaland innovation are not merely parallel determinants of international trade but are deeply synergistic forces. They form a virtuous cycle: a highly skilled workforce drives innovation, and the process of innovation, in turn, creates demand for even more advanced skills, thereby shaping what and how a nation trades. This cycle propels developed economies towards specialization in high-value-added, knowledge-intensive goods and services, allowing them to maintain a competitive edge despite higher labor costs and intense global competition (Baldwin,

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2016).
Classical and modern trade theories have evolved to recognize the role of human capital in determining comparative advantage. Traditional models, such as the Heckscher-Ohlin framework, emphasized factor endowments like labor and capital. However, contemporary extensions incorporate human capital as a key driver of trade specialization, especially in skill-intensive goods and services (Findlay and Kierzkowski, 1983; Unel, 2015). The endogenous growth theory further posits that human capital accumulation not only enhances productivity but also facilitates the diffusion of technology and innovation across borders, amplifying the gains from trade (Fatima et al., 2020; Rahman and Alam, 2021).
Human capital shapes international trade both directly—by enabling high-skilled workers to benefit from globalization while low-skilled workers face greater adjustment costs—and indirectly, by fostering innovation and absorptive capacity, which are essential for export sophistication and competitiveness in developed economies (Fagerberg, 1988; Acemoglu & Autor, 2011).
Human capital and innovation play a crucial role in reducing $CO_2$ intensity in international trade by enabling the development and adoption of cleaner technologies and more efficient production processes; higher levels of education and innovative capacity are consistently linked to lower emissions, while trade openness can increase $CO_2$ unless supported by strong human capital and innovation policies that promote sustainable growth (Lin et al., 2021; Dauda et al., 2020; Khan et al. 2025; Mahmood et al., 2019) In the context of trade, new trade theory and the theory of comparative advantage suggest that countries with higher levels of human capital and innovation can specialize in and export more sophisticated, less carbon-intensive goods, thereby improving both economic performance and environmental outcomes
The intellectual groundwork for this relationship was laid by endogenous growth theorists, most notably Romer (1990) and Lucas (1988), who formally embedded human capital and knowledge creation at the core of economic growth models. Romer's (1990) theory argued that technological change—endogenized through investments in R&D and human capital—is the primary driver of growth, fundamentally shifting the focus from exogenous factors. This theoretical revolution naturally extended to international trade, suggesting that nations capable of continuous innovation would develop dynamic comparative advantages in new, high-tech industries (Grossman &Helpman, 1991).
The central focus of this research is that the interplay between human capital and innovation along with $CO_2$ intensity is the fundamental engine driving the evolution of international trade patterns for developed nations (Jan et al.2025). So, the current study investigated the impact of human capital, innovation and $CO_2$ intensity on international trade in the context of developed countries.

## Literature Review
An increasing body of literature emphasizes the importance of innovation and human capital in influencing international trade patterns between developed nations. The present review consolidates recent studies on such associations. Innovations, especially technological progress, are a key to improving international competitiveness and trade performance of developed nations. Technological innovation, such as renewable energy and energy efficiency technologies, has been found to have a positive effect on trade by advancing productivity and allowing nations to provide higher-quality goods and services in international markets. Trade is also a driver of additional innovation, and a vicious circle is created where international market openness generates technological progress and vice

versa (Atsu & Adams, 2023; Shevchenko & Omelyanenko, 2025). Nevertheless, the effect of innovation on trade tends to be mediated by the availability of human capital with skills and expertise as well as favorable institutional environments (Atsu & Adams, 2023). Human capital as the ability, education, and knowledge of the labor force is an essential driver of value-added trade in global value chains (GVCs) in industrial nations. Increased levels of human capital in both the exporting and importing countries significantly increase bilateral trade volumes, particularly in industries involving sophisticated knowledge and skills. The beneficial impact of human capital is especially evident in advanced economies, where highly skilled labor is fundamental for manufacturing and exporting high-technology, complicated goods (Shevchenko & Omelyanenko, 2025; Wang & Thangavelu, 2021). Human capital also increases the absorptive capacity for new technologies, further tying together the relationship between trade and innovation. The interplay between innovation and human capital is critical to ongoing trade competitiveness. High-income countries that invest in human capital development and innovation infrastructure are in a better position to respond to global problems, update their production modes, and keep up their competitive advantage in global markets. Strategic human resource development, education modernization, and skills alignment with innovation objectives are all highlighted as avenues for international trade maximization benefits (Kurteš et al., 2023a; Shevchenko & Omelyanenko, 2025).

Furthermore tariffs, subsidies, and interest rates also help shape international trade dynamics in developed economies. Tariffs remain a central instrument in trade policy, with significant effects on trade flows, supply chains, and economic welfare. Recent studies show that higher tariffs on imported goods in developed economies reduce both GDP and consumer welfare, especially when tariffs target sectors central to domestic production networks (Kreuter & Riccaboni, 2023). Tariffs also negatively impact participation in global value chains, as their effects cascade through supply chains, amplifying the initial trade barriers and reducing sectoral integration (Yanikkaya et al., 2024). While tariffs can be used to protect domestic industries, they often lead to trade volume reductions, lower income, and can trigger retaliatory measures, resulting in trade wars with substantial long-term macroeconomic costs (Kreuter & Riccaboni, 2023; Shapiro, 2020). In the context of green supply chains, tariffs increase retail prices and reduce product greenness and social welfare, but these negative effects can be partially offset by consumer preferences for green products (Yi & Wen, 2023).

Subsidies, including direct payments, tax incentives, and government procurement, are widely used to support domestic industries and promote policy goals. In developed economies, subsidies can modestly increase trade volumes, as seen in the dairy sector, though their effects may be short-lived. Industrial subsidies, particularly in high-tech sectors, can improve national welfare and competitiveness, and may generate less distortion than tariffs if properly implemented (Ju et al., 2024; Kondaridze & Luckstead, 2023). In transnational supply chains, government subsidies can increase product quality, profits, and social welfare, and effectively mitigate the negative impacts of tariffs (Yi & Wen, 2023). However, subsidies can also distort trade and investment flows, undermine tariff bindings, and contribute to global trade tensions, prompting increased regulatory scrutiny and calls for international cooperation (Athayde et al., 2023; Ur Rahman et al.2014).

This study contributed in the existing literature with the role of interest rate in the international trade. While direct recent evidence on the impact of interest rates on international trade in developed economies is limited in the latest literature, interest rates generally influence trade by affecting exchange rates, investment, and the cost of capital.

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Lower interest rates can stimulate exports by depreciating the domestic currency and reducing financing costs for exporters, while higher rates may have the opposite effect. Therefore, the interaction between monetary policy and trade policy remains an important area for further research.

## Data and Method

### Model Specification

This research has designed the given below specification to empirically analyze the impact of human capital, innovation and $CO_2$ intensity on international trade in case of developed economies following ….

$TRA\ 1(resi + nonresi)_{it} = \beta_1 HCI_{it} + \beta_2 INT_{it} + \beta_3 INO_{it} + \beta_4 INDUS_{it} + \beta_5 CO2_{it} + \beta_6 TR_{it} + \beta_7 subi_{it} + \varepsilon_{it}$……………………………………….1.1

$TRA\ 2(\%\ GDP)_{it} = \beta_1 HCI_{it} + \beta_2 INT_{it} + \beta_3 INO_{it} + \beta_4 INDUS_{it} + \beta_5 CO2_{it} + \beta_6 TR_{it} + \beta_7 subi_{it} + \varepsilon_{it}$…………………………………………………….1.2

$TRA\ 3\ (EXP + IMP)_{it} = \beta_1 HCI_{it} + \beta_2 INT_{it} + \beta_3 INO_{it} + \beta_4 INDUS_{it} + \beta_5 CO2_{it} + \beta_6 TR_{it} + \beta_7 subi_{it} + \varepsilon_{it}$……………………………………….1.3

where the variables of interest in all 3 models are stated as follow: $\text{TRA1(resi + nonresi) = trade (resident + nonresident), TRA2(resi + nonresi) = trade (resident + nonresident), TRA3(resi + nonresi) = trade (resident + nonresident), HCI = human capital, INT = INT rate, INO = INO, INDUS = industrilization, CO2 = co2 intensity, TR = tarrif , subsi = subisidies.}$

## Results and Discussion

**Table 1: Descriptive analysis:**

| Variable | Obs | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|
| **TR1** | 1,615 | 9.842332 | 1.594648 | 4.317488 | 13.77255 |
| **HCI** | 1,784 | 0.674121 | 0.107316 | 0.293705 | 0.887084 |
| **INT** | 1,287 | 5.570952 | 17.35526 | -88.4603 | 202.5567 |
| **TR** | 2,046 | 5.911541 | 6.395927 | -11.5 | 39.96 |
| **INO** | 860 | 5.34E-11 | 0.960348 | -2.2567 | 2.385899 |
| **INDUS** | 1,429 | 7.000594 | 2.28277 | 0 | 11.97587 |
| **CI** | 1,815 | 2.449948 | 1.13746 | -1.15624 | 13.28205 |
| **SUBSI** | 1,952 | 23.26999 | 3.071722 | 13.3486 | 32.69397 |

Descriptive statistics provide important insights into the distribution and variability of the economic variables being studied. The variable "TR1" has a mean of 9.8423 and a standard deviation of 1.5946, suggesting that trade activities in the residential and non-residential sectors largely cluster around this average but vary significantly, as shown in the range of 4.3175 to 13.7726. Human Capital Investment (HCI) follows a fairly regular pattern across data, with a mean of 0.6741 and a low standard deviation of 0.1073, indicating that most locations or periods have comparable amounts of human capital investment, ranging from 0.2937 to 0.8871.

INT rates vary significantly, with a mean of 5.5710 and a large standard deviation of 17.3553. The large range, from -88.4603 to 202.5567, suggests that some locations faced severe economic situations, such as very high or very low (or negative) INT rates. TRrates vary significantly, with a mean of 5.9115 and a standard deviation of 6.3959, ranging from -11.5 to 39.96. This implies that, while most regions have positive TRs, some may have negative TRs, which could reflect SUBSI or trade incentives.

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INO levels, with a mean close to zero (5.34E-11) and a standard deviation of 0.9603, vary greatly from -2.2567 to 2.3859, demonstrating significant disparities in INO between locations or periods. The logarithm of INDUS has a mean of 7.0006 and a standard deviation of 2.2828, with values ranging from 0 to 11.9759, indicating varied degrees of INDUS, from little or none in some places to high levels in others. $CO_2$ intensity has a mean of 2.4499 and a standard deviation of 1.1375, with a range of -1.1562 to 13.2821, indicating moderate variability in carbon emissions, with certain places having much greater or lower levels of $CO_2$ intensity.

**Table 2: Correlation matrix**

| | TRA | HCI | INT | TR | INO | INDUS | $CO_2$ | SUBSI |
|---|---|---|---|---|---|---|---|---|
| **TRA** | 1 | | | | | | | |
| **HCI** | 0.4981 | 1 | | | | | | |
| **INT** | -0.084 | -0.2227 | 1 | | | | | |
| **TR** | -0.4004 | -0.566 | 0.0159 | 1 | | | | |
| **INO** | 0.1949 | 0.7679 | -0.1987 | -0.0304 | 1 | | | |
| **INDUS** | 0.8157 | 0.37 | -0.1758 | -0.2958 | 0.2039 | 1 | | |
| **$CO_2$** | -0.3403 | -0.3253 | 0.013 | 0.3549 | -0.4262 | -0.0776 | 1 | |
| **SUBSI** | 0.636 | 0.4376 | -0.1334 | -0.3812 | 0.194 | 0.5724 | -0.2314 | 1 |

The correlation matrix identifies numerous important links between the variables. The log of trade (residential and non-residential) has a substantial positive association with INDUS (0.8157) and SUBSI (0.636), implying that increased INDUS and tax incentives are linked to higher trade volumes. Furthermore, there is a moderate positive connection with human capital investment (0.4981), implying that greater investment in human capital leads to increased commerce. In contrast, trade levels are inversely connected with TRs (-0.4004) and $CO_2$ intensity (-0.3403), indicating that greater TRs and $CO_2$ emissions are associated with less trade.

Human capital investment has a substantial positive association with INO (0.7679), implying that regions that invest more in human capital are more innovative. There are also positive connections with INDUS (0.37) and SUBSI (0.4376), implying that more human capital investment leads to increased industrial activity and tax advantages. However, human capital investment has a negative connection with INT rates (-0.2227) and TRs (-0.566), meaning that greater investment in human capital leads to lower INT rates and TRs.

**Table 3: Cross sectional dependency:**

| |
|---|
| Pesaran's test of cross sectional independence = 0.647, Pr = 0.5174 |
| Average absolute value of the off-diagonal elements = 0.345 |
| Friedman's test of cross sectional independence = 22.286, Pr = 0.0729 |
| Frees' test of cross sectional independence = 1.495 |
| Critical values from Frees' Q distribution |
| alpha = 0.10:0.3583; alpha = 0.05:0.4923; alpha = 0.01: 0.7678 |

Pesaran's Test of Cross-Sectional Independence: The test statistic is 0.647, and the p-value

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is 0.5174. This high p-value indicates that we are unable to reject the null hypothesis of cross-sectional independence, implying that the data contains no substantial evidence of cross-sectional dependency (Pesaran, 2004).

Friedman's Test of Cross-Sectional Independence: The test statistic is 22.286, and the p-value is 0.0729. While this p-value is somewhat higher than the standard 0.05 threshold, it is close enough to raise concerns about cross-sectional dependence, particularly in circumstances where a more lenient significance level (e.g., 0.10) is appropriate (Friedman, 1937).

The Frees' Test of Cross-Sectional Independence has a test statistic of 1.495. When compared to the critical values from Frees' Q distribution, it exceeds all (0.3583 for $\alpha = 0.10$, 0.4923 for $\alpha = 0.05$, and 0.7678 for $\alpha = 0.01$). This result clearly shows that the data has cross-sectional dependence (Frees, 1995).

The average absolute value of the off-diagonal elements is 0.345, showing a moderate correlation between cross-sectional units. This lends credence to the occurrence of some degree of cross-sectional dependence, which is consistent with the findings of Frees' test. The findings of Pesaran's test indicate no substantial cross-sectional reliance, whilst Frees' test implies the contrary, with the Friedman test providing equivocal evidence. This mismatch shows that cross-sectional reliance is context-specific or that various tests have varying sensitivities. This disparity shows that cross-sectional dependence may be context-specific, or that different tests are sensitive to the structure of the data. Given Frees' test's strong suggestion of dependency, you may want to account for any cross-sectional dependence in your model to avoid skewed estimates.

**Table 4: Unit root test**

| Variable name | Lags | T*value |
|---|---|---|
| **HCI** | 0 | -0.84082 |
| **HCI** | 1 | -6.76738*** |
| **CI** | 0 | -7.02425*** |
| **CI_1** | 1 | -105.927*** |
| **INO** | 0 | -4.93447*** |
| **INO_1** | 1 | -13.0404*** |
| **INDUS** | 0 | -5.64243*** |
| **INDUS** | 1 | -52.1048*** |
| **TR1** | 0 | -21.4462*** |
| **TR1** | 1 | -50.2801*** |
| **TR2** | 0 | -12.5748*** |
| **TR2** | 1 | -58.3667*** |
| **TR3** | 0 | -2.90226*** |
| **TR3** | 1 | -32.1904*** |
| **TR** | 0 | -0.48816 |
| **TR** | 1 | -36.4955*** |
| **INT** | 0 | -8.65282*** |
| **INT** | 1 | -32.5723*** |
| **SUBSI** | 0 | -12.8090*** |
| **SUBSI** | 1 | -20.1757*** |

The panel unit root test results show differing degrees of stationarity across the variables.

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Human Capital Investment (HCI) is non-stationary at lag 0, with a t-value of -0.84082, but becomes stationary after one lag, as evidenced by a highly significant t-value of -6.76738. $CO_2$ Intensity is firmly stationary during the current period (t-value of -7.02425) and after one lag (t-value of -105.927), indicating a stable series. INO is also stationary, with significant t-values at lags 0 (-4.93447) and 1 (-13.0404). Similarly, INDUS exhibits substantial stationarity in both periods, with t-values of -5.64243 at lag 0 and -52.1048 at lag 1.
The trade variables, which include trade (residential and non-residential) and trade percentage (TR2), are extremely stationary, with significant t-values at both lags 0 and 1. Trade (imports and exports) also exhibits stationarity; however, its t-value at lag 0 (-2.90226) is less strong than that of other variables, but it becomes strongly stationary after one lag (t-value of -32.1904).
TRis non-stationary at lag 0, as evidenced by a non-significant t-value of -0.48816, but becomes stationary after one lag, with a very significant t-value of -36.4955.
INT rates and SUBSI are both stationary over time, with extremely significant t-values at lags 0 and 1. Overall, these findings indicate that, while the majority of variables are stationary and suitable for study, others, such as HCI and TR, may require differencing or other adjustments to attain stationarity before being included in time series models.

**Table 5: Pooled Mean Group (PMG) Results**

| | **TR1** | **TR2** | **TR3** |
|---|---|---|---|
| **HCI** | -7.764* | 37.46*** | 0.73 |
| | (-2.54) | 3.37 | 1.29 |
| **INT** | -0.0017 | -0.114*** | -0.00920*** |
| | (-0.14) | (-3.48) | (-3.52) |
| **TR** | -0.303*** | -0.0957 | -0.0424** |
| | (-7.33) | (-1.89) | (-3.20) |
| **INO** | 0.743** | 1.769*** | -0.212*** |
| | 3.07 | 4.92 | (-3.32) |
| **INDUS** | 0.780*** | 0.586*** | -0.138*** |
| | 6.48 | 3.47 | (-4.54) |
| **CI** | 1.986*** | 1.71 | -0.031 |
| | 6.19 | 1.27 | (-0.49) |
| **SUBSI** | -0.824* | 0.995 | -0.0372 |
| | (-2.10) | 1.42 | (-0.30) |
| **ECT** | -0.168*** | -0.0642 | 0.200** |
| | (-3.95) | (-1.21) | 3.03 |
| **C** | 6.281*** | -0.474 | -1.161** |
| | 3.68 | (-0.96) | (-2.99) |
| **N** | 375 | 399 | 399 |
| **Wald test** | 53.34*** | | |

The empirical results of PMG regression show that HCI has a negative influence on commerce (both residential and non-residential) with a coefficient of -7.764 (t = -2.54*), implying that increasing investment in human capital may lower this sort of trade. However, HCI has a positive impact on trade percentage (37.46, t = 3.37***), implying that increased human capital investment could boost the economy's overall trade share, most likely through enhanced productivity. INT rates have a negative impact on TR2 (-0.114, t = -3.48***) and trade (exports and imports) (-0.00920, t = -3.52***), indicating that higher interest rates tend to lower trade activity due to higher financing costs. The negative impact of human capital investment on trade may appear surprising. However, this could be consistent with research indicating that increased investment in human capital moves focus away from conventional sectors and toward more knowledge-intensive industries, thereby limiting trade in sectors that rely on less trained workers (Anar Mammadov, Ilyas Veliev, 2024). (Rees, 1965) show that investments in education and skills increase productivity, resulting in a more competitive trading market. This shows that human capital investment improves trade competitiveness even while it does not immediately increase trade volumes.

TRs are discovered to have a considerable negative impact on both commerce (residential and non-residential) (-0.303, t = -7.33***) and trade (exports and imports) (-0.0424, t = -3.20**), corroborating the traditional belief that higher TRs discourage trade by boosting the cost of imported goods. TRs have a consistent negative impact on trade, particularly in which is consistent with the extensive research on trade barriers. According to (Krugman, 1992), TRs diminish trade volume by raising the cost of imported goods, resulting in a decline in both imports and exports as countries retaliate with levies.

INO has a positive influence on residential and non-residential trade (0.743, t = 3.07**) as well as trade percentage (1.769, t = 4.92***), implying that INO promotes domestic commerce and raises trade's portion of the economy. However, it has a negative impact on trade (exports and imports) (-0.212, t = -3.32***), suggesting a move toward more domestic-focused production. The beneficial impact of INO on trade as a percentage is consistent with studies that show how INO improves a country's comparative advantage. These studies contend that INO leads to the creation of new products and processes, which improves trade competitiveness. However, the negative impact on overall trade may reflect the disruptive character of INO in specific industries. (Christensen, 2015) addresses how INO can often lead to the demise of existing industries as new technologies replace old ones, lowering commerce in conventional sectors.

INDUS has a positive impact on trade (residential and non-residential) (0.780, t = 6.48***) and trade percentage (0.586, t = 3.47***), implying that it increases trade activity. However, it has a negative influence on trade (exports and imports) (-0.138, t = -4.54***), which may indicate a decrease in reliance on international markets as domestic output grows. $CO_2$ Intensity has a significant effect on commerce (residential and non-residential) (1.986, t = 6.19***), showing that higher $CO_2$ emissions are related with increased domestic trade, but not on other trade metrics. The useful impact of INDUS on residential and non-residential trade, as well as trade percentages, is consistent with traditional economic theories that link modernization to greater production capacity and exports (Lewis, 1954). Industrialized economies often have more diverse and competitive trade portfolios, increasing trade volumes and shares. However, the negative impact on overall trade could be traced to the structural changes that come with INDUS. As economies transition from agriculture to industry, they may temporarily lessen their reliance on imports while shifting production focus to the domestic market (Shen et al., 2021).

SUBSI have a negative impact on trade (residential and non-residential) (-0.824, t = -2.10*), but their impacts on TR2 are insignificant, implying that SUBSI largely influence domestic trade activities rather than overall trade flows. The beneficial effect of INDUS on residential and non-residential trade, as well as trade percentages, is consistent with classic economic theories linking modernization to increased production capacity and exports (Lewis, 1954). Industrialized economies frequently have more diverse and

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competitive trade portfolios, resulting in higher trade volumes and shares. However, the negative impact on overall trade might be attributed to the structural changes associated with INDUS. As nations migrate from agriculture to industry, their reliance on imports may temporarily decrease while production shifts to the domestic market (Shen et al., 2021).

The Error Correction Term (ECT) reveals the presence of long-term equilibrium relationships, with significant coefficients for residential and non-residential trade (-0.168, t = -3.95***) and trade (exports and imports) (0.200, t = 3.03**), indicating that deviations from long-term equilibrium are corrected over time. The considerable error correction term in the residential and non-residential trade models indicates that trade volumes are adjusting toward long-term equilibrium, which is consistent with trade dynamics research (Engle & Granger, 1987). This suggests that short-term deviations from equilibrium are adjusted over time, resulting in trade pattern stability.

Overall, the Wald test result of 53.34*** indicates that the model is statistically significant and has a good fit to the data. These findings highlight the complex linkages between economic variables and trade, implying that policymakers should carefully consider these aspects when creating measures to improve trade competitiveness and control trade dynamics.

**Table 6: Dynamic Fixed Effects Regression: Estimated Error Correction Form**

| **variable** | **TR1** | **TR2** | **TR3** |
|---|---|---|---|
| **HCI** | -9.465* | -4.297 | -2.282* |
| | (-2.07) | (-1.42) | (-2.16) |
| **INT** | 0.0112 | 0.0127 | -0.00374 |
| | 0.58 | 1.26 | (-1.06) |
| **TR** | 0.00265 | 0.0591 | -0.0011 |
| | 0.02 | 0.91 | (-0.05) |
| **INO** | 1.096* | 0.348 | 0.230* |
| | 2.25 | 1.23 | 2.38 |
| **INDUS** | 1.406*** | -0.18 | -0.0446 |
| | 8.63 | (-1.94) | (-1.36) |
| **CI** | .11 | -1.260*** | -0.085 |
| | 0.21 | (-3.89) | (-0.76) |
| **SUBSI** | -0.953 | 2.873*** | 0.216 |
| | (-1.12) | 7.14 | 1.59 |
| **ECT** | -0.129*** | -0.100*** | -0.178*** |
| | (-7.29) | (-7.35) | (-6.14) |
| **C** | 5.182 | -1.434 | 0.216 |
| | 1.95 | (-1.35) | 0.33 |

The Dynamic Fixed Effects Regression model explains how various economic variables influence different trade measures. The variable Human Capital Investment (HCI) yields mixed results. A significant negative impact on commerce (residential) (-9.465, t = -2.07*) indicates that greater human capital investment may diminish residential commerce, maybe due to shifts in focus or increased productivity in other industries. However, the lack of a significant impact on trade percentage (-4.297, t = -1.42) and the negative effect on trade (exports and imports) (-2.282, t = -2.16*) suggest that human capital investment may influence overall trade dynamics but not consistently modify trade proportions. The

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conflicting outcomes for human capital investment reflect its multifaceted influence in trade dynamics. The large negative impact on residential trade may be due to a shift in economic focus. Countries that invest in human capital frequently reallocate resources to more knowledge-intensive industries, potentially at the expense of traditional residential commerce. (Shevchenko & Omelyanenko, 2025) claims that increasing human capital investment might result in structural economic shifts that move focus from less productive to more sophisticated industries. The lack of a significant impact on TR2 and the negative effect on global trade indicate that, while human capital investment has an impact in some regions, it does not consistently affect trade proportions (Rees, 1965).

INT rates have no meaningful impact on any of the trade measures. The coefficients for Trade (residential) (0.0112, t = 0.58), Trade percentage (0.0127, t = 1.26), and Trade (exports and imports) (-0.00374, t = -1.06) are all close to zero and statistically insignificant, implying that INT rates have little immediate impact on trade activities in this context. The model finds that INT rates have no meaningful impact on any of the trade measures, which is consistent with some current work but contradicts others. According to (Leblang, 2003), INT rates can have an impact on commerce by altering borrowing costs and investment. However, the findings suggest that INT rates have little influence on trade activity in this particular economic environment. This could indicate that other variables, such as INO or INDUS, have a greater impact on commerce than capital costs.

TRs are likewise of minimal significance. TRs may not have a substantial impact on trade (residential) (0.00265, t = 0.02) or trade percentage (0.0591, t = 0.91), as indicated by the coefficients. Trade (exports and imports) has a negative coefficient (-0.0011, t = -0.05), indicating that TRs have little effect on trade volumes. TRs have a minor impact on trade metrics, particularly on trade implying that TRs may not be a major predictor of trade dynamics in this model. (Krugman, 1992) stated that TRs often restrict trade by raising the cost of imported goods. The model's result that TRs have a minor effect on trade volumes suggests that other factors, such as INO or INDUS, may be more crucial in deciding trade outcomes in this scenario.

INO has a considerable favorable influence on both residential trade (1.096, t = 2.25*) and export and import trade (0.230, t = 2.38*). This suggests that greater INO benefits trade by increasing competitiveness and productivity. However, the effect on TR2 is not statistically significant (0.348, t = 1.23), implying that the impact of INO on trade proportions may be less evident. The strong positive impact of INO on both domestic and international trade (exports and imports) emphasizes its importance in improving trade competitiveness. (Kurteš et al., 2023b) suggest that INO drives comparative advantage, resulting in more commerce. The positive impact on trade volumes but not on trade percentage may indicate that, while INO increases overall trade, its impact on the proportion of trade relative to other economic activities is less direct. INO can cause shifts in industry dynamics, resulting in the collapse of conventional industries while increasing overall trade competitiveness (Christensen, 2015).

INDUS has a high positive influence on Trade (residential) (1.406, t = 8.63***), showing that it greatly increases residential trade activity. However, the effects on TR2 (-0.18, t = -1.94) and trade (exports and imports) (-0.0446, t = -1.36) are less significant, implying that while INDUS improves domestic commerce, its impact on total trade metrics may be less obvious. The considerable beneficial impact of INDUS on residential trade is compatible with traditional economic theories, by (Lewis, 1954), which link modernization to greater production capacity and exports. The model suggests that INDUS considerably boosts domestic trade activity, possibly due to greater production and diversity. However, the less significant effects on trade suggest that, while INDUS

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stimulates internal commerce, its impact on broader trade metrics may be more nuanced. This could be due to a transitory reduction in import reliance when countries change from agricultural to industry, as proposed by (Shen et al., 2021).
$CO_2$ Intensity has a negative (-1.260, t = -3.89***), impact on TR2 indicating that higher $CO_2$ emissions are connected with a lower trade percentage, maybe due to regulatory limits or increased production costs. The effects on trade (residential) (0.11, t = 0.21) and trade (exports and imports) (-0.085, t = -0.76) are not significant, implying that $CO_2$ intensity's effect on trade dynamics may be indirect. The negative correlation between $CO_2$ intensity and trade percentage suggests that higher emissions are connected with a lower proportion of trade, most likely due to environmental controls or increased production costs. This finding is backed by the pollution haven theory, which states that tougher environmental laws might diminish trade competitiveness in polluting businesses. However, the lack of a significant impact on residential and overall commerce shows that $CO_2$ intensity's effect on trade dynamics may be indirect, impacting trade via regulatory or cost channels rather than directly altering trade quantities.
SUBSI have a substantial positive effect on TR2 (2.873, t = 7.14***), indicating that larger SUBSI lead to more commerce in the economy. The effects on trade (residential) (-0.953, t = -1.12) and trade (exports and imports) (0.216, t = 1.59) are not statistically significant, demonstrating that SUBSI have a greater impact on trade proportions than absolute trade volumes. The significant positive effect of SUBSI on TR2 suggests that bigger SUBSI can encourage trade, which is consistent with (Kondaridze & Luckstead, 2023) claim that tax incentives can attract investment and improve trade. The lack of significance in residential trade and overall trade metrics shows that SUBSI may have a greater impact on trade proportions than absolute quantities. This could imply that, while tax breaks are successful in boosting trade, they have a greater impact on relative trade dynamics than on total trade volume.
The Error Correction Term (ECT) is significant across all trade measures, with negative coefficients (Trade (residential): -0.129, t = -7.29***; Trade percentage: -0.100, t = -7.35***; Trade ((exports and imports) -0.178, t = -6.14***), demonstrating the model's effectiveness in correcting deviations from long-term equilibrium and ensuring trade relationship stability over time.

## Conclusion

The study has carried out the empirical analysis of HC and INO with trade using PMG regression in the panel of developed economies. In the empirical analysis, INT and TR are robustly significant in the reduction of trade activities while INO and INDUS are strongly significant to promote trade of developed nations. HCI has significantly increased trade GDP ratio of these nations. The estimates of HC, INT and TR in the dynamic regression are unexpected while the coefficients of INO, INDUS, and SUBSID are giving the robustness to the PMG regression's coefficients. Significant ECTs demonstrate the model's robustness in addressing long-term trade dynamics.
The empirical results conclude that INO, INDUS, and HCI are closely related drivers that boost international trade in advanced economies in a very effective way. Education at high levels, skills, and development of the workforce raise labor productivity, facilitate research and development (R&D), and make possible the adoption and diffusion of new technology. This, in return, increases the ability of businesses and countries to compete in international markets and engage in sophisticated global value chains (Anar Mammadov, Ilyas Veliev, 2024; Carillo, 2024). Technological progress and successful innovation systems, frequently driven by qualified human capital, give rise to increased-value outputs and more

productive production processes. This enhances export competitiveness and enables advanced nations to hold a dominant role in global trade (Kurteš et al., 2023a). Industrialization also leverages the positive impact of human capital and innovation on trade by ensuring sectors that are increasingly export-oriented and technology-intensive (Shen et al., 2021).
Interest rates, tariffs, and subsidies are important policy instruments that influence international trade results in advanced economies, each having unique impacts and trade-offs. Tariffs, in developed countries, tend to distort and lower the flow of trade, especially between advanced and developing nations. More intensive tariffs can destroy global value chains and reduce aggregate trade efficiency, hence becoming a less efficient instrument for supporting trade in sophisticated economies (Arshad et al., 2023; Islam et al., 2024). Nonetheless, in certain strategic situations, precisely aimed tariffs might briefly enhance importer well-being or offset foreign market dominance, but such advantages are frequently outweighed by more general reductions in trade and possible retaliation (McCalman, 2023). Properly designed industrial subsidies can increase national welfare, promote high-technology industries, and enhance competitiveness with less distortion than tariffs. Subsidies can also counteract adverse foreign market power effects and, in conjunction with tariff changes, can strongly underpin domestic industry and trade performance (Ju et al., 2024). Interest rates, though, have relatively direct recent evidence of their effect on trade, as they operate by influencing exchange rates and the cost of capital. Lower rates can encourage exports by making local products more competitive and lower the cost of financing for exporters, whereas increasing rates can slow down trade activity (Cheng & Chen, 2025).

**Suggestions**

Recent research emphasizes the need for prospective policies that could concurrently stimulate innovation and human capital improvement to raise international trade performance. Trade liberalization, education investment, and research and development support are suggested in order to maintain growth and competitiveness in developed economies.

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