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Analyzing the complexities of export: a heterogeneous analysis of BRICS economies and product types

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Abstract

This study examines the determinants of export sophistication across BRICS countries (Brazil, Russia, India, China, and South Africa) from 2000 to 2022. It focuses on the heterogeneous effects of macroeconomic variables economic growth (GDP), foreign direct investment (FDI), human capital, and research and development (R&D) as well as the impact of the COVID-19 pandemic on export sophistication. The study employs the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) approach, which effectively captures cross-sectional dependence and slope heterogeneity, improving upon traditional panel estimation techniques. The empirical findings indicate that GDP growth, FDI inflows, human capital, and R&D expenditures positively influence export sophistication in BRICS economies, while the COVID-19 pandemic exerts a negative effect. These insights offer important policy implications for enhancing export quality and economic resilience in emerging markets.

Keywords Export, Export sophistication, COVID-19, Bilateral FDI, R&D

Introduction

In the contemporary global economy, international trade plays a central role in economic development, growth, and market expansion. A country's economic strength is often reflected in the volume and quality of its exports, which generate foreign exchange, stimulate innovation, and support long-term economic sustainability. To maintain global competitiveness, policymakers increasingly emphasize export sophistication as a strategic instrument for enhancing growth and resilience. Export sophistication refers to a nation's ability to produce and export high value-added and technologically advanced goods, reflecting economic diversification and structural upgrading.

Economies specializing in sophisticated exports tend to achieve higher income levels, increased foreign exchange reserves, and stronger national income growth. Diversification toward high-value exports also enhances economic resilience by reducing vulnerability to external shocks. Moreover, export sophistication promotes technological progress and innovation, requiring sustained investment in human capital and research and development. A skilled workforce enables productivity gains and supports participation in global value chains, facilitating access to advanced technologies and international markets. China's transformation into a leading exporter of sophisticated products, particularly in renewable energy, electronics, and automotive components, illustrates the growth-enhancing role of export upgrading.

Economic growth, measured by GDP, plays a critical role in shaping export sophistication. GDP reflects overall economic health and supports investments in diversification and innovation. The relationship

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between GDP and export sophistication is bidirectional. While diversification contributes to economic growth, higher income levels also enable economies to shift toward more complex exports. Empirical evidence suggests that export diversification and manufacturing intensity significantly promote GDP growth, particularly in developing and emerging economies [3], Muralidharan & Sridharan, 2022; [42, 43]. Foreign direct investment further strengthens export sophistication by transferring capital, technology, and managerial expertise to domestic industries. Studies highlight FDI as a key determinant of export upgrading and export substitution, particularly in technologically intensive sectors [19], Kannen, 2020 [33]; [8]. Similarly, human capital remains fundamental to productivity and export performance. Consistent with the Solow–Swan growth framework, labor quality alongside capital accumulation drives economic growth. Investment in education enhances innovation capacity, adaptability, and international competitiveness [14].

Research and development expenditures also play a crucial role in upgrading export structures. R&D investment improves production processes, fosters innovation, and strengthens competitiveness, especially in high-tech industries. Evidence suggests that R&D, capital deepening, knowledge spillovers, and institutional quality jointly promote export sophistication [8].

Global trade interdependence has also exposed economies to systemic shocks, most notably the COVID-19 pandemic. Since early 2020, COVID-19 has disrupted supply chains, reduced demand, and constrained international connectivity, significantly affecting export-oriented industries (Eichenbaum et al., 2020) [22]. For BRICS economies, these disruptions weakened trade linkages and altered export dynamics across pandemic waves (Jareno et al., 2023). Against this backdrop, this study focuses on BRICS economies to examine the effects of economic growth, human capital, FDI, R&D, and COVID-19 on export sophistication. BRICS countries provide a compelling case due to their heterogeneous growth trajectories, large population share, expanding role in global trade, and increasing engagement in trade liberalization and foreign investment. Collectively accounting for nearly 42 percent of the global population and approximately 23 percent of world GDP, these economies have emerged as major destinations for FDI and key contributors to global production networks. Understanding the determinants of export sophistication in BRICS economies offers valuable insights for policymakers seeking to enhance competitiveness and economic resilience in an increasingly interconnected global economy.

Theoretical framework

This study draws upon several foundational theories in international trade, development economics, and innovation to explain the determinants of export sophistication. Export sophistication is conceptualized as a function of economic growth, innovation capacity, human capital development, and foreign knowledge spillovers. The following theories provide the basis for the study's conceptual model:

Product life cycle theory [64]

The Product Life Cycle (PLC) theory posits that products pass through stages: introduction, growth, maturity, and decline. In the context of international trade, Vernon suggests that developed countries initially innovate and export standardized, low-cost products. As technology diffuses and production becomes more routine, these products are eventually manufactured in developing countries. Over time, nations accumulate learning, capital, and skills, allowing them to shift from exporting low-tech goods to more advanced, high-value products. This transition underpins the concept of export sophistication, as countries evolve along the technological ladder [64].

Endogenous growth theory [58]

Endogenous growth models emphasize the role of internal factors such as technological innovation, human capital accumulation, and knowledge creation in driving long-term economic performance. Romer [58] argues that policies promoting education, R&D, and innovation have compounding effects on productivity. These dynamics are directly linked to export sophistication, as economies that invest in innovation are more likely to produce complex, high-value goods, thereby improving their export structure.

Knowledge spillover and technology diffusion theory [1, 19]

This perspective highlights the role of foreign direct investment (FDI) as a key channel through which developing countries acquire advanced technologies, managerial know-how, and best practices. Dunning's eclectic paradigm (OLI framework) suggests that multinational enterprises bring proprietary knowledge and innovation to host countries. These spillovers improve domestic firms' productivity and their ability to engage in more sophisticated exports [19]. Recent studies such as Ali and Malik (2022) confirm that financial development and FDI are critical in spreading productivity-enhancing knowledge across.

The integration of these theoretical perspectives provides a strong conceptual foundation for this study's

investigation into the determinants of export sophistication in BRICS economies. The Product Life Cycle Theory supports the view that nations evolve in their export structures, moving from basic commodities to more advanced, value-added goods as they develop technologically an evolution clearly observable within the BRICS bloc. The Endogenous Growth Theory underscores the role of internal drivers such as human capital development, innovation, and R&D core variables in this study in enhancing productivity and enabling countries to produce more sophisticated exports. Meanwhile, the Knowledge Spillover and Technology Diffusion Theory justifies the inclusion of FDI, suggesting that international investment facilitates the transfer of advanced technologies and practices to local firms, enhancing their export capabilities. Lastly, the Learning-by-Doing and Capability Building approach aligns with the idea that export sophistication emerges not just from inputs, but from experiential processes and the accumulation of knowledge, particularly relevant to emerging economies seeking to scale up their technological and industrial competencies. Collectively, these theories inform the model used in this study and provide the rationale for the selection of variables that aim to capture both structural and external influences on export sophistication.

Literature review

This section of research paper explains the impact of various factors impacting export sophistication. These factors include GDP of the country, FDI, research and development, COVID-19 and human capital. They are discussed as follows:

Aditya and Acharyya [3] investigated the export–economic–growth relationship at the export and country level. They find that both diversification and composition of exported goods have detrimental impact on economic growth. The critical level of export concentration beyond which increasing export specialization leads to higher growth has also been estimated. Additionally, they find that growth of technology-oriented goods contributes to output growth, particularly for countries with a higher share of manufacturing exports. Shirazi and Manap [60] examined the export-led growth hypotheses for the 5 selected countries in the South Asian region. In their research, it was discovered that with the exception of Sri Lanka, there is a long-term link between exports, imports, and real production. Additionally, exports and GDP are correlated in both directions for Bangladesh and Nepal, while exports are solely responsible for Pakistan's economic expansion. Jarreau & Poncet [32] looked at the functional link between economic development and export sophistication in China for the same reason. They discovered evidence to back up the claim that areas with higher-end product specializations experience quicker economic growth. The association between taxing practices and economic complexity in OECD nations was examined by Lapatinas et al. [39]. Their findings imply that disparities in nations' capacities to develop and export more complex goods can be explained by taxing policy. Olubiyi [48] investigated the causal relationship between real GDP and exports with other macroeconomic variables in the case of Nigeria. The study confirmed feedback hypothesis between real GDP and exports (See [15, 59], Ahmed & Salam, 2018; [34, 57] for similar results). In the existing literature, the impact of bilateral foreign direct investment (FDI) on export sophistication has been widely discussed. This section of literature review aims to examine the existing research on the relationship between FDI and export sophistication. These heterogeneous adoption dynamics mirror differences observed across BRICS economies and product types, suggesting that structural, technological, and institutional diversity shapes both digital finance adoption and export-related outcomes [24]. In similitude of Jarreau and Poncet [32], Eck and Huber [21] analyzed the impact of FDI on the product sophistication of firms in India. They found that spillovers from multinational firms through supplier linkages strongly increased the manufacturing of sophisticated products by local firms. This suggests that FDI can contribute to enhancing the export sophistication of a country. By analyzing the panel data of various countries, Tebaldi [63] found that inflows of FDI and trade liberalization were major factors in increasing the performance of high-tech industry of the countries in the global market. This indicates that FDI plays a role in promoting the export of technologically advanced and export sophistication. Mukhtarov et al. [47] examined how FDI affected Jordan's exports. Their findings suggested that FDI had a long-term, statistically significant beneficial influence on exports. The study concluded that a 1% rise in foreign direct investment results in 0.13% increase in exports. This found that FDI can accelerate export sophistication through promoting value-added goods of export sophistication.

Increase in research and development activities is also a way to sophisticate export. It has been concluded in many studies in the prevailing literature that delivers insights into the relationship between the roles of R&D in export sophistication. Likewise, Barrios et al. [13] has investigated the significant of firm's own R&D activity and spillovers effect on the decision to export and its intensity. The authors found that a firm's own R&D activity was a significant factor of determining export activity, and that it is directly affected through the industrial's export ratios. This suggests that R&D enhance export sophistication by improving the quality and complexity

of exported products. Similarly, Sousa et al. [62] studied on the determinants of export performance. Their review highlighted the importance of various factors in influencing export performance in addition to the focus on research and development. This suggests that R&D, as one of the determinants, can potentially impact export sophistication. Jarreau & Poncet [32] examined the effect of export sophistication on economic performance in China. They found evidence supporting the hypothesis that regions specializing in more sophisticated goods experience due to R&D activities fasters economic growth. Mostafiz et al. [45] highlighted the role of training and development in promoting creativity and flexibility in decision-making in export of manufacturing industries. Their findings suggest that investments in human capital and knowledge spillover through R&D can sustain export sophistication. In similitude, the study of Zapata et al. [70], the factors affecting of high-tech exports has been studied in the case of OECD countries. They have concluded that some policy variables including: inward foreign direct investment, R&D expenditure, and imports of high-tech manufactures, were significant determinants of technology-oriented exports. Countries with tax policies that rely less on capital relative to labor tend to produce more complex products, while countries with tax policies that rely heavily on capital produce simpler products. This implies that the policy structure can influence a country's ability to develop and export sophisticated products boosted by foreign R&D activities. Other studies have also touched on related aspects. Ellis [23] explored how exposure to affluent overseas consumers and rivals through exporting might provide domestic companies better access to knowledge about new trends, shifting consumer preferences and competitive activities, which can affect the creation of market orientation. The importance of training and development in fostering innovation and adaptability in decision-making in export manufacturing enterprises was underlined by Mostafiz et al. [45]. Mayneris & Poncet [44] examined the role of foreign export spillovers on the creation of new export linkages, suggesting that initiatives to diffuse best practices regarding export experience among exporters can be beneficial. In summary, while there is limited research specifically focusing on the impact of foreign R&D on export sophistication, existing studies suggest that factors such as target market characteristics, taxation policies, exposure to foreign customers and competitors, and training and development can influence export sophistication and its relationship with economic performance. Further research specifically examining the role of foreign R&D in driving export sophistication would provide valuable insights into this area. The impact of human capital on export sophistication has been examined in several studies. The existing literature provides insights into the affiliation between human capital and export sophistication. Koopman et al. [38] document the rise in export sophistication in China and suggest that it may be evidence of an increase in the level of sophistication embedded in the country's exports. They highlight the fear that China's production and export of sophisticated products may provide wage competition for mid-to-high-skilled workers in the US and Europe.

Goldberg & Pavcnik [28] discuss the distributional effects of trade liberalization and found that skilled labor gets more benefits by shifting productivity toward technology. Tebaldi [63] examines the elements that determine high-tech exports and comes to the conclusion that human capital, foreign direct investment inflows, and trade openness are important variables that affect how well a nation's high-tech industry performs on the international market. This indicates that human capital is vital to the production and export of sophisticated goods. The research indicates that human capital has a positive effect on export sophistication. Dossani & Kenney [17] discussed the role of offshoring services in the value-addition and sophistication export in India. The authors highlight those exports of services requires skillful and educated human capital, as it is different than that of the origins of exported goods from developing nations. According to Agosin et al. (2011) [4], increasing human capital benefits export diversification. Higher human capital countries can boost export diversification by utilizing favorable terms of trade shocks. More advanced training and development can foster innovation and flexibility in decision-making in export manufacturing enterprises, according to Mostafiz et al. [45]. The impact of human capital on the export performance of Pakistani small and medium-sized businesses (SMEs) was studied by Mubarik et al. [46]. In particular for medium-sized businesses and those with medium to high levels of export intensity, they discovered that human capital, particularly education and training, had a direct and indirect influence on export success. The association between taxing practices and economic sophistication was examined by Lapatinas et al. [39]. They discovered that economies with lower capital taxes relative to labor taxation tend to create more sophisticated and complex goods. The structure of taxation, which affects the allocation of resources, can influence a country's capacity to produce and export sophisticated products. Zapata et al. [70] highlighted the positive impact of human capital on technology-intensive exports. Higher levels of human capital are associated with an increase in the production and export of high-tech products. Madonna & Handoyo [43] examined the effect of innovation, logistic performance, and human capital on the export diversification

of the manufacturing industry. They found that good quality human capital contributes to the specialization of goods for export and can transform raw goods into manufactured goods with higher value. Similarly, Wang et al. [66] analyzed the effect of intellectual capital on Chinese exporters' performance. They found that intellectual capital generates dynamic capabilities, which, in turn, improve overseas export performance. Risk management capability also plays a complementary mediating role in enhancing export performance. Atasoy [8] identified various determinants of export sophistication, including human capital. Human capital accumulation, improvement in education expenditures, and promotion of human capital were found to be positively correlated with export sophistication. The existing literature has also highlighted impact of COVID-19 pandemic on global value chains, stock markets and the growth performance of export-oriented firms. Likewise, in the study of Gereffi [27], he analyzed the impact of the COVID-19 pandemic on global value chains in the medicine industry. He concluded that the Pandemic-19 has surged demand for medical goods, whereas due to lockdown causing shortages, and disruptions in exports of goods and services due to the interdependence of international trade. Similarly, the study of Song and Zheng (2022) [61] has also investigated the reaction of stock markets resulting decline in the export of BRICS countries due to the outbreak of the COVID-19 pandemic. However, the studies also emphasize the importance of resilience, diversification, and governmental support in mitigating the negative impacts and promoting recovery in export sophistication. Grant & Beckman (2022) [7] evaluate the reaction of stock markets in BRICS countries to the outbreak of the COVID-19 pandemic. The study finds that while agricultural trade remained stable, the sector as a whole did not go unscathed, with certain commodities being more severely impacted. Kočenda & Poghosyan [37] analyze the determinants of export sophistication using a dynamic panel data approach. The study finds that output and country size positively impact export sophistication, while human capital and land area do not exhibit statistically significant effects. Atasoy [8] investigated the determinants of export sophistication, with a special focus on the effects of digitalization. The study finds that exports become more sophisticated as digitalization promotes, and institutional quality, access to credit, and R&D are concluded to be other drivers of export sophistication. Yan et al. [69] propose a hybrid machine learning approach for international carbon price forecasting. The study focuses on the Emissions Trading System (ETS) in the EU and equivalent models in China, finding that sophisticated algorithms perform well in predicting carbon prices. Heinzová et al. [29] map and analyze the development of small and medium enterprises' exports during the COVID-19 pandemic in the Czech Republic. The study confirms the statistically significant impact of the pandemic on the decline in exports and identifies the most significant export risks. Ishaq et al. [31] investigate the impact of COVID-19 on the growth performance of export-oriented firms in Pakistan. The study finds that the pandemic has impacted firms' operations, supply chains, and labor retention, with technology adoption proving to be a dominant strategy for survival. Liu et al. [42] examine the relationship between export sophistication and total factor energy efficiency under climate change. The study finds that export sophistication improvement leads to higher total factor energy efficiency. Rahman et al. [54] examine the role of export diversification in mitigating the adverse effects of the COVID-19 pandemic in Malaysia. The study suggests that export diversification plays a vital role in minimizing the disruptive effect of the pandemic on exports. Number of COVID-19 cases and fatalities compared to bilateral export and import rates of mechanical items is analyzed by Khorana et al. [36]. According to their findings, the prevalence of reported cases and fatalities of COVID-19 in nations that export goods likely played a significant role in reducing global trade. Overall, the literature suggests that the COVID-19 pandemic has had significant impacts on export sophistication in BRICS countries.

Extensive Literature regarding export sophistication and its driving forces has been widely discussed in the former section. Like, Aditya & Acharyya [3] find that export sophistication positively impacts economic growth, and technology-oriented goods contribute to output growth and export. Other studies highlighting the role of economic growth are Shirazi and Manap [60], Jarreau & Poncet [32], Sanjuan & Dawson, [59], Belloumi & Alshehry [15], Ahmed & Sallam [5] and Romero [57]. Moreover, the role of FDI in export sophistication can't be ignored. Like Jarreau & Poncet [32] and Eck and Huber [21] demonstrated the significant role of Foreign Direct Investment (FDI) in enhancing export sophistication (See [21, 32, 47, 63] for similar results). R&D activities are also identified and discussed as key factors in improving the quality and complexity of exported products [13, 32, 43]. Moreover, some studies like, Koopman et al. [38], Goldberg & Pavcnik [28], Dossani & Kenney [17] and Tebaldi [63] have also discussed human capital as important determinant in enhancing export sophistication of the country. [17, 38, 63]. The COVID-19 pandemic has had notable impacts on global value chains and export-oriented firms [27],Chavali et al., 2021). Ishaq et al. [31] reveal that technology adoption was a dominant strategy for survival for export-oriented firms in Pakistan during the pandemic. In response to the pandemic's effects,

resilience and diversification strategies are emphasized to promote recovery in export-oriented industries. Hence, keeping into view the existing literature, no study has been conducted to model the impact of GDP, foreign direct investment, investment in research & development activities and COVID-19 pandemic on export sophistication in the case of BRICS economies. In this study, we attempt to cover such research gap by analyzing the heterogeneous impacts of these variables.

While a substantial body of literature has explored the determinants of export sophistication, most studies have focused either on developed countries or have examined individual variables in isolation. For instance, previous research has investigated the roles of economic growth [3, 32], FDI [21, 63], human capital [28, 38], and R&D [13, 70] as independent drivers of export upgrading. However, few studies have examined the combined and interactive effects of these variables within a single, unified framework—particularly in the context of emerging economies.

Moreover, there is a noticeable scarcity of empirical studies focusing on BRICS economies as a collective group. These countries present a unique opportunity for comparative analysis, given their distinct economic trajectories, policy environments, and export patterns. While individual BRICS countries—such as China or India—have been the subject of export-focused research, there remains a clear gap in literature addressing the heterogeneous dynamics of export sophistication across the full BRICS bloc.

An additional shortcoming in the existing research is the limited treatment of exogenous shocks such as the COVID-19 pandemic. Although some recent studies (e.g., [27, 29]) have discussed pandemic-related trade disruptions, they rarely model these effects empirically in the context of export sophistication.

Research gap and contribution

This study addresses these gaps by proposing a comprehensive empirical model that integrates macroeconomic drivers GDP, FDI, R&D, and human capital alongside a COVID-19 pandemic dummy variable, to explain export sophistication in BRICS economies over the period 2000–2022. Furthermore, we applies first time the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) approach, which accounts for both cross-sectional dependence and slope heterogeneity—two critical issues often overlooked in traditional panel methods. This allows for more accurate estimation of long-run relationships and country-specific dynamics. A few recent studies such as Ben Youssef and Dahmani [11] used the CS-ARDL approach to examine how digitalization, environmental tax revenues, and energy resource capacity affect environmental quality across 88 countries. For a panel of ASEAN-5 economies, Ayyash [2] applies CS-ARDL to explore income inequality dynamics by focusing on GINI-based determinants. These studies confirms that accounting for cross-sectional dependence and heterogeneous slopes improves long-run inequality estimates. Given the aforementioned studies, we argue that CS-ARDL approach is best fit for our study and a novel contribution to the literature in term of research study.

Data and methodology

Data and model specification

To empirically examine the determinants of export sophistications, the basic model is specified as:

$$ESI_{i,t} = \lambda_1 GDP_{i,t} + \lambda_2 FDI_{i,t} + \lambda_3 R\&D_{i,t} + \lambda_4 HC_{i,t} + \mu_{i,t} \quad (1)$$

where in Eq. (1), ESI represents export sophistication index, GDP represents Gross Domestic Product, FDI is foreign direct investment, R&D represents research and development expenditures and HC represents human capital. In Eq. (1), "i" is for cross-sections such as Brazil, Russia, India, China, and South Africa, and "t" is the period.

This study also examines the impact of COVID-19 on the export sophistication of BRICS nations; hence, we include the dummy variable of COVID-19 in the empirical model (2). The extended model (2) is given as:

$$\begin{aligned} ESI_{i,t} = {} & \varphi_1 GDP_{i,t} + \varphi_2 FDI_{i,t} + \varphi_3 R\&D_{i,t} \\ & + \varphi_4 HC_{i,t} + \varphi_4 DUM_{COVIDi,t} + \mu_{i,t} \end{aligned} \quad (2)$$

where DUM_{COVID} represents COVID dummy.

Analytical techniques

Cross-section dependence (Cd) and slope heterogeneity (Sh) tests

Before applying unit root and cointegration tests, this research first checked for the issues of cross-section dependence (CD) and slope heterogeneity (SH). Ignoring either of these concerns raises the risk of producing inaccurate or ineffective findings. As a result, we employ the cross-section dependence test developed by Pesaran [50]. This test's null hypothesis presupposes that cross-section units are uncorrelated and that cross-sectional groups alternately depend on one another for support. The economic and demographic makeup of different nations can also be rather distinct. Due to the potential

inefficiency of the homogeneity assumption, the slope heterogeneity assumption is checked using the Pesaran and Yamagata [52] test. The null hypothesis assumes uniformity, while the alternative predicts variation.

Panel unit root tests

It is crucial to employ stationarity tests that can handle both heterogeneity and cross-section dependence, as these will be the first concerns to be investigated in this research. First, the stationarity test developed by Im et al. [30] is applied, as it is compatible with the heterogeneity of ρ_i. However, this approach cannot handle cross-sectional dependency among cross-sectional units. Therefore, cross-sectionally augmented Im, Pesaran, and Shin (CIPS), as proposed by Pesaran [51], should be utilized for stationary behavior checking as it is a more robust approach. As the method addresses the issue of varying slope and cross-sectional dependence among cross-section units such as Brazil, Russia, India China and South Africa, it is able to produce effective outcomes. The equation for CPS is given as:

$$\Delta W_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \overline{W}_{t-1} + \sum_{l=0}^{p} \varphi_{il} \Delta \overline{W_{t-l}} + \sum_{l=1}^{p} \varphi_{il} \Delta W_{i,t-l} + \tau_{it} \quad (3)$$

where $\overline{W}_{t-1}$ and $\Delta \overline{W_{t-l}}$ are the cross-section averages. The CPS is shown as:

$$\widehat{CPS} = \frac{1}{N} \sum_{i=1}^{n} CDF_i \quad (4)$$

Equation (3) can be used to determine the value of the cross-sectionally augmented dickey fuller (CDF).

Equation (4) shows the CPS final panel unit root test statistic for Pesaran's CIPS test.

Westerlund [68] cointegration method

Long-run cointegration in the presence of heterogeneity and cross-section dependence necessitates the use of a suitable test, as has been argued before. That's why we employ the cointegration approach proposed by Westerlund [68]. Two group statistics (G_t and G_a) and two panel statistics (P_t and P_a,) are provided by this technique. Cointegration throughout the entire sample can be analyzed using group statistics, whereas cointegration across all of the cross-sections—including Brazil, Russia, India, China and South Africa—can be analyzed using panel statistics.

Cross-sectionally augmented autoregressive distributed lags (CS-ARDL)

Traditional autoregressive distributed lag (ARDL) models are inadequate when trying to account for cross-sectional variation. To address this issue, the CS-ARDL approach was created. To account for differences in observations, it combines the strengths of combined cross-sectional data with those of time series analysis. A two-stage estimation method, CS-ARDL combines cross-sectional and time series data. Before estimating the ARDL model as a whole, we first use time series data from each cross-section unit (here, each of the BRICS economies).

In order to represent the dynamics of the system, the ARDL model often makes use of lagged dependent variables and pertinent explanatory variables. Second, the estimated coefficients from each separate ARDL model are combined to provide the CS-ARDL estimates. Parameter estimates are improved through the aggregation process, which takes into account cross-sectional heterogeneity. CS-ARDL is especially helpful for studying the complexity and heterogeneity of exports across the BRICS nations in this research since it allows for the examination of the relationship between variables while accounting for cross-sectional differences. Furthermore, the CS-ARDL approach allows for variable delays for each cross-sectional unit, adjusting to varied dynamics in the time series data, giving more freedom in selecting the optimal lag length. By combining time series and cross-sectional data, CS-ARDL enhances the efficiency of the estimates, which can result in more precise conclusions and trustworthy policy suggestions. Due to the several benefits accrue from using the CS-ARDL strategy proposed by Chudik and Pesaran [16] for both long- and short-term outcomes, this study utilize CS-ARDL technique over others including the pooled mean group (PMG), the common correlated mean group (CCEMG), the mean group (MG), and the augmented mean group (AMG). The key features that set it apart from the previously described methods are: 1) its effectiveness in endogeneity and heterogeneity and 2) cross-sectional reliance, which aids in achieving productive outcomes. 3) Using structural breaks effectively is helpful [16]. To address the issue of dependence among cross-section units, it introduces cross-section averages. The equation is written out below:

Table 1 Description of Variables, Abbreviations, Sources, and Time Coverage

Variable	Abbreviation	Definition	Data Source	Time Period
Export Sophistication Index	ESI	Measures the technological level and complexity of exported goods	UNCTAD/World Bank (EXPY-based index)	2000–2022
Gross Domestic Product	GDP	Real GDP per capita (constant 2010 US$), indicator of economic growth	World Bank (World Development Indicators)	2000–2022
Foreign Direct Investment	FDI	Net inflows of FDI as % of GDP	UNCTAD/World Bank	2000–2022
Research and Development	R&D	Expenditure on R&D as % of GDP	UNESCO Institute for Statistics / World Bank	2000–2022
Human Capital	HC	Human Capital Index (education and health components)	Penn World Table / World Bank	2000–2022
COVID-19 Dummy	DUMCOVID	Dummy variable (0 = pre-COVID years; 1 = 2020–2022)	Constructed by Authors (based on WHO pandemic declaration)	2000–2022

Table 2 Results of diagnostic tests (Cross-section dependence and slope heterogeneity tests)

Variables	CD-statistics	*P*-values
ESI	13.53***	0.000
GDP	5.42***	0.000
FDI	16.23***	0.000
R&D	18.29***	0.000
HC	21.28***	0.000

Table 3 Slope heterogeneity test results

Statistic	Values	*P*-values
Delta-tilde	9.265***	0.000
Delta-tilde-Adjusted	11.385***	0.000

*** is for significance level < 0.01

$$\Delta CO_{2,i,t} = \varphi_i + \sum_{l=1}^{p} \varphi_{il} \Delta CO_{2,i,t-l} + \sum_{l=0}^{p} \varphi_{il}{}' EV_{s,i,t-l} + \sum_{l=0}^{1} \varphi_{il}{}' \overline{CSA}_{i,t-l} + \varepsilon_{i,t} \quad (5)$$

In Eq. (5), cross-sectional averages (CSA) is represented by $\overline{CSA}_t = \left(\Delta\overline{CO}_{2,t}, \overline{EV}_{s,t}{}'\right)'$, EV's variables are placed at the right side of the equations. Following Eberhardt [20], the robustness for the results performed is checked through the augmented mean group (AMG) which is helpful for cross-section dependence problem and heterogeneity.

Results and discussion

This study checks the CD and SH by using advance techniques. Table 1 shows the test statistics of CD, and Table 2 shows slope homogeneity (SH) tests. It is evident that all variables are cross-sectionally dependent. Hence, all variables are cross-sectionally interrelated. A shock in one of the variables in any BRICS nations has repercussion for the same variable in other BRICS nations.

Table 1 provides a summary of all variables used in the study, including their abbreviations, definitions, data sources, and time coverage from 2000 to 2022. It ensures transparency and clarity in the construction of the empirical model.

The results shows that both models suffer from slope heterogeneity which can be seen from the p value in Table 3 that's statistically significant.

Due to the problems of CD and SH, this study uses CIPS unit root test which are given in Table 4. The results of CIPS unit root test in Table 4 show that the variables

Table 4 Results of unit root test (cross-sectionally augmented Im, Pesaran and Shin test)

Variables	Level		First difference		Outcome
	constant	Trend and constant	constant	Trend and constant	
ESI	− 2.51**	− 2.91***	–	–	I(0)
GDP	− 1.89	− 2.17	− 3.85***	− 3.97***	I(1)
FDI	− 2.41*	− 3.61***	–	–	I(0)
R&D	− 1.81	− 1.83	− 3.83***	− 4.01***	I(1)
HC	− 2.91***	− 3.72***	–	–	I(0)

***, **, * is for *P*-values < 0.01, 0.05 & 0.10

are mix order of integration. It is evident that ESI, FDI and HC are stationary at level while the variables GDP and R&D are stationary at first difference.

In the next step, this study uses Westerlund [68] cointegration test to check the long-run relationship among variables of model 1 and model 2,as mentioned in Table (5). The results suggest that the variables of model 1 and model 2 have a long-term nexus with ESI.

Next, we estimate model 1 and model 2 by CS-ARDL method. The results of CS-ARDL method (reported in Table 6) indicate that GDP, FDI, R&D and HC positively affect ESI in case of BRICS nations. However, the coefficient of DUM_{COVID} is negative and significant at 1% level, which suggest that COVID-19 has negative impact on ESI in case of BRICS nations. The negative and significant coefficients of lagged error correction term in both models suggest that the variables of model 1 and model 2 have a long-term nexus with ESI.

As the empirical outcomes of this study (reported in Table 6) show that GDP has a significant positive effect on export sophistication in BRICS nations. These outcomes show that the economic growth in BRICS economies significantly improved export sophistication. Exports that are more complicated and have greater value-added tend to emerge with a growing GDP, which is a reflection of rising economic activity, productivity, and competitiveness. The export sophistication of the BRICS countries can benefit from a growing GDP in a number of ways. As a first indicator of a healthy domestic market, it may inspire businesses to spend more on R&D and incorporate cutting-edge tools and techniques into their manufacturing workflows. Companies that priorities innovation and technological development are able to produce more high-end and marketable products [37] second, an expanding economy usually means more money to spend and higher consumer demand. Increased consumption has the potential to generate demand for a wide variety of items, including those with greater complexity. This could encourage domestic businesses to improve their export sophistication by expanding and modernizing their capabilities to serve the needs of both domestic and foreign markets [32]. Further, increased GDP paves the way for more spending on HC-related activities like education and training. Companies with access to skilled and educated labor forces can undertake more intricate production processes and create novel products, both of which can elevate the quality of their exports. This renewed commitment to HC growth promotes the accumulation of specialized skills, which in turn boosts international competitiveness [10]. This underscores the significance of continuous economic growth, innovation, investment in R&D, and the development of human capital in the BRICS economies, where GDP has a favorable impact on export sophistication. All of these things work together, to make the BRICS countries more prosperous and competitive on the global market by increasing the sophistication and value of their exports. These results confirm the findings of [9, 40].

Moreover, the result of CS-ARDL method (reported in Table 5) further show that foreign direct investment (FDI) has a favorable effect on export sophistication in BRICS nations, which is indicative of the positive association between FDI and the development of more advanced exports. Foreign direct investment (FDI) offers a number of benefits that can help these countries raise the bar on the quality of their exports. To begin with, foreign direct investment (FDI) attracts new sources of money, technology, and managerial skills. This infusion of funds provides businesses with the opportunity to get access to cutting-edge manufacturing methods, novel technologies, and international best practices, all of which have the potential to vastly improve their output. Companies that implement these innovations will be able to create more high-quality and complex items, making them more competitive internationally [56]. Similarly, FDI frequently results in the development of inter firm networks and ties. These relationships allow for the spread of information and new technologies, as well as access to foreign markets. Companies in their home country benefit from increased familiarity with international markets, consumer tastes, and business practices when they work with or are acquired by foreign corporations. Because of this,

Table 5 Westerlund-Cointegration test

	Statistics	G_t	G_a	P_t	P_a
Model 1	Values	− 4.69***	− 9.32***	− 10.49***	− 8.29***
Model 2	Values	− 6.21***	− 10.47***	− 12.29***	− 10.36***

*** is for significance level < 0.01

Table 6 CS-ARDL's Estimates (Dependent Variable: ESI)

Variables	Coefficients of Model 1		Coefficients of Model 2	
	Coefficients	*P*-values	Coefficients	*P*-values
GDP	0.418***	0.002	0.528**	0.017
FDI	0.254*	0.053	0.317*	0.074
R&D	0.093*	0.085	0.085*	0.083
HC	0.194***	0.000	0.185***	0.000
DUM_{COVID}	…	…	− 0.073***	0.000
ECM (-1)	− 0.51***	0.000	− 0.53***	0.000

***, **, * is for *P*-values < 0.01, 0.05 & 0.10

exports have become more refined as producers have adapted their products to match the needs of other markets (Ozsoy et al., 2021[49]). Foreign direct investment (FDI) also helps domestic industries and supply chains. The presence of foreign investors in a given industry helps pave the way for the growth of related businesses. Increased export quality is a byproduct of this complex network of industries, which fosters productivity gains, economies of scale, and specialization [41]. Therefore, the beneficial effect of FDI on export sophistication in BRICS economies highlights the value of foreign investment in modernizing production capacities, transferring technology, and opening access to global markets. In order to boost their exports' complexity and competitiveness and, in turn, boost their economies, the BRICS countries must attract and make good use of foreign direct investment (FDI). These results confirm the findings of [65].

Similarly, the result of CS-ARDL method (reported in Table 6) show that HC positively effect ESI in BRICS economies, Because of the favorable effect of HC on export sophistication in BRICS economies, it is clear that a highly educated and trained labor force is essential to the growth of sophisticated exports. Knowledge, skills, education, and training are all examples of human capital, and they all play a role in a country's ability to generate competitive commodities. As cutting-edge manufacturing practices can't be adopted or implemented without a labor force that is both educated and skilled. With the help of HC, businesses are able to fully leverage the benefits of mechanization, automation, and digital technology in their manufacturing operations. Using these methods, businesses can boost efficiency and output while also creating more high-quality exports [53]. In the foot, a highly skilled workforce is more likely to partake in R&D activities and propel innovation. To create new items, enhance old ones, and boost production techniques, innovation is essential. Skilled individuals working in the scientific and technological fields can create new ideas, conduct research, and help differentiate products, all of which can increase the value of exports. A culture of continuous learning and information sharing can be encouraged by placing a premium on HC development, which includes funding educational and training initiatives. When people learn new things, they add to the collective economic resource of expertise. The workforce isn't the only one that can reap the rewards of this knowledge spillover effect,other industries can also stand to gain from it as it helps to foster an economy that is more integrated and innovation-driven. A country's ability to specialize in specific industries and advanced sectors is boosted by having a competent labor force. Workers who invest in their own professional development are better able to contribute to the manufacturing of high-quality, cutting-edge products. Export sophistication and the capacity to fulfill the demands of international markets can be greatly enhanced through specialization and competence in specific industries [55]. Therefore, the importance of investing in education, skill-building, and knowledge accumulation is highlighted by the favorable effect of human capital on export sophistication in BRICS economies. The ability of a country to innovate, specialize in high-value industries, generate high-quality exports, and embrace cutting-edge technologies is bolstered by the presence of a highly educated and trained labor force. The BRICS countries can boost their economic growth and competitiveness in the global market by investing in their people. These results confirm the findings of [67].

In the same foot, Innovation and technical progress play a significant role in driving the development of high-quality, innovative, and sophisticated exports, as evident by the positive significant coefficient of research and development (R&D) (reported in Table 5). By encouraging the development of new products, the refinement of current ones, and the improvement of production methods, R&D helps boost the BRICS nations' competitiveness in the global market. Businesses are able to benefit from new scientific discoveries and cutting-edge technologies because of investments in research and development. Companies can conduct innovative research, try out new ideas, and create ground-breaking technologies by setting aside funds for research and development (R&D). These developments have the potential to greatly improve the quality, usefulness, and sophistication of exported products, making them more appealing to consumers in other countries [26]. Moreover, intellectual property like patents and copyrights are born out of research and development. Companies are more likely to invest in research and development when they know they will profit from their efforts. Firms in the BRICS economies are investing more in R&D and becoming more technologically advanced as a result of the improved protection of intellectual property. Research and development also encourage information sharing and new ideas among the BRICS nations. Collaboration, information sharing, and the development of new ties between academics from diverse domains are all conditions favorable to the growth of new ideas. This ecosystem helps to create and spread knowledge, best practices, and technology improvements that may increase export sophistication across industries [9]. The BRICS economies' investments in R&D also aid the growth of niche markets and niche service providers. Businesses can get a leg up on the

competition by investing in R&D to develop groundbreaking new products or processes. The export competitiveness of these economies is driven by their ability to manufacture unique, innovative, and high-quality goods. The export market can be expanded by investment in R&D. The BRICS countries may better meet the needs of niche international markets by investing in R&D. This would allow them to capitalize on emerging opportunities in the global economy. This broadens the export sophistication of these economies while reducing their reliance on a small number of export products [71]. Ultimately, the importance of innovation and advancements in technology in encouraging the creation of high-quality and inventive exports is shown by the favorable effect of R&D on sophistication in BRICS economies. The BRICS countries may boost their economic growth and international competitiveness by investing in research and development. This will allow the countries to do things like foster technical advances, promote intellectual property protection, foster innovation ecosystems, stimulate specialization, and diversify exports. These results confirm the findings of [25].

On the contrary, the results of CS-ARDL method (reported in Table 5) show negative and significant coefficient of DUM_{COVID}, which suggest that COVID-19 has negative impact on ESI in case of BRICS nations. There are a number of ways to look at the damage COVID-19 has done to the BRICS countries' ability to export technologically sophisticated goods. As COVID-19 caused disruptions in supply chains around the world, raw materials and intermediate items became scarce. Because of this setback, BRICS nations were unable to keep up or improve the level of sophistication of their exports. Due to production delays or material shortages, output dropped and quality deteriorated. The demand for non-essential commodities, which frequently make up a large portion of exports from BRICS countries, dropped significantly as the epidemic prompted economic downturns and a concentration on vital items [35]. Moreover, Export sophistication suffered as a result of the drop in demand, forcing businesses to either lower output or focus on producing only the bare necessities. In addition, as a result of the worldwide economic slowdown brought on by COVID-19, both consumer purchasing power and investment spending fell. Because of the decline in demand, many BRICS countries lowered the prices at which they sold their exports. When prices drop, it could be because consumers no longer see as much value in what they're buying [18]. In addition, there was a substantial impact on BRICS transport and logistics networks due to COVID-19-induced travel bans and lockdown measures. Delays in shipping and delivery of commodities caused by a lack of access to transportation networks and restrictions on international trade, impacted export sophistication by lowering the dependability and timeliness of exports (reference). The epidemic also hampered the BRICS countries' ability to learn, adopt, and develop cutting-edge technologies by disrupting technology transfer and reducing international collaboration on research and development. Because of this, progress was slowed, and fewer high-quality export goods were made. In addition, COVID-19 has altered purchasing habits and tastes by emphasizing necessities, technology, and healthcare more than ever before. The demand for several products that have historically been exported by the BRICS countries has decreased as a result of this preference shift [6]. Overall, supply chain disruptions, decreased demand, a depressed global economy, travel and logistical constraints, limited access to technology and innovation, and a shift in consumer tastes have all contributed to the detrimental impact of COVID-19 on export sophistication in BRICS countries. Collectively, these limitations have impeded the BRICS countries' ability to develop and export more sophisticated and high-value goods. These results confirm the findings of [12].

For robustness check, this study uses the augmented mean group (AMG) method. The estimates of AMG (reported in Table 7) are consistent with the estimates of CS-ARDL. It is evident that GDP, FDI, R&D and HC positively affect ESI in case of BRICS nations. However, the coefficient of DUM_{COVID} is negative and significant at 1% level, which suggests that COVID-19 has negative impact on ESI in case of BRICS nations.

Table 7 Robustness Results using augmented mean group (AMG)

Variables	Coefficients of Model 1	Coefficients of Model 2
GDP	0.376*** (0.064)	0.385*** (0.052)
FDI	0.142*** (0.017)	0.175*** (0.012)
R&D	0.093*** (0.011)	0.126*** (0.008)
HC	0.019*** (0.003)	0.027*** (0.001)
DUM_{COVID}	…	− 0.265*** (0.002)
Constant	4.154*** (0.037)	3.219*** (0.046)

***, **, * is for *P*-values < 0.01, 0.05 & 0.10. () shows standard errors

Conclusion and policy recommendations

This study provides robust evidence that export sophistication in BRICS economies is significantly influenced by several key factors, including GDP growth, foreign direct investment (FDI), research and development (R&D) investments, and human capital development. The positive correlations found in the analysis suggest that economic expansion, increased foreign investment, innovation-driven activities, and the development of a skilled workforce collectively enhance the ability of these countries to produce more complex and higher-value exports. Such export sophistication is critical for improving global competitiveness and fostering sustainable economic development. However, the study also highlights the detrimental impact of the COVID-19 pandemic, which disrupted global trade networks, lowered demand for certain products, and strained supply chains. These disruptions have temporarily constrained the BRICS countries' capacity to upgrade the complexity of their exports, emphasizing the vulnerability of their export structures to global shocks.

Building on these findings, the study underscores the importance of comprehensive policy measures that can sustain and accelerate export sophistication in the BRICS economies.

- First, governments are encouraged to focus on broad economic growth strategies, including infrastructure development, business-friendly regulations, and entrepreneurship support, to strengthen the foundation for advanced exports.
- Secondly, attracting FDI through clear policies and incentives, investing in R&D especially in export-oriented sectors, and enhancing human capital via targeted education and training programs—particularly in STEM fields—are also essential.
- Thirdly, diversifying export markets and reinforcing supply chain resilience are crucial to reduce the negative effects of exogenous shocks like the COVID-19 pandemic. By pursuing these multifaceted strategies, BRICS nations can improve their economic resilience, elevate their export capabilities, and better position themselves in the global marketplace for long-term prosperity.

While the current model effectively captures key relationships between the selected variables, it is important to acknowledge certain limitations regarding variable selection and model scope. The variables included in this study were chosen based on theoretical relevance, prior empirical evidence, and data availability. However, this selection inevitably excludes other potentially influential factors that may affect the outcomes. For instance, [mention any relevant variables not included, e.g., socioeconomic status, environmental factors, etc.] were not incorporated due to data constraints or scope limitations. Despite these constraints, the model demonstrates robust performance and provides valuable insights into the phenomena under investigation. The chosen variables balance complexity with interpretability, ensuring the model remains tractable and actionable for the target audience.

Future research could extend this framework by incorporating additional variables, such as [list potential variables or data types], which may improve explanatory power and allow for more nuanced analyses. Additionally, alternative modeling approaches—such as machine learning techniques or longitudinal designs—could be explored to better capture nonlinearities and dynamic effects. Overall, while the current model serves as a solid foundation, expanding variable scope and methodological sophistication represents a promising direction for further study.

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Kafeel: Write original draft, data curation, conceptualization, research methodology, and data analysis. Martin Hronec: Review and editing (equal), supervision, project administration, resources. Jana Hroncova Vicianova: Review and editing (Equal), supervision, project administration. Sher Khan: Review and editing (Equal), supervision, structuring. Marian Suplata: Review and editing (Equal). Each author made significant contributions to the work, ensuring a comprehensive and collaborative effort. All authors reviewed the manuscript and agree to publish this work.

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References

1. Ali N, Malik ZK (2022) Knowledge spillover and total factor productivity across countries: role of financial development. Pak J Soc Res 4(04):494–501
2. Ayyash, M. (2025). *Income inequality dynamics in ASEAN-5: A panel data investigation using CS-ARDL* [Article]. (retrieved from Springer platform)
3. Aditya A, Acharyya R (2013) Export diversification, composition, and economic growth: evidence from cross-country analysis. J Int Trade Econ Dev 7(22):959–992. https://doi.org/10.1080/09638199.2011.619009
4. Agosin MR, Alvarez R, Bravo-Ortega C (2012) Determinants of export diversification around the world: 1962–2000. World Econ 35(3):295–315
5. Ahmed O, Sallam W (2018) Studying the volatility effect of agricultural exports on agriculture share of GDP: the case of Egypt. Afr J Agric Res 8(13):345–352. https://doi.org/10.5897/ajar2016.11920
6. Ali SRM, Mensi W, Anik KI, Rahman M, Kang SH (2022) The impacts of COVID-19 crisis on spillovers between the oil and stock markets: evidence from the largest oil importers and exporters. Econ Anal Policy 73:345–372
7. Arita S, Grant J, Sydow S, Beckman J (2022) Has global agricultural trade been resilient under coronavirus (COVID-19)? Findings from an econometric assessment of 2020. Food Policy 107:102204
8. Atasoy B (2020) The determinants of export sophistication: does digitalization matter? Int J Fin Econ 4(26):5135–5159. https://doi.org/10.1002/ijfe.2058
9. Atasoy BS (2021) The determinants of export sophistication: does digitalization matter? Int J Financ Econ 26(4):5135–5159
10. Baliamoune-Lutz M (2019) Trade sophistication in developing countries: does export destination matter? J Policy Model 41(1):39–51
11. Ben Youssef A, Dahmani M (2024) Assessing the impact of digitalization, tax revenues, and energy resource capacity on environmental quality: fresh evidence from CS-ARDL in the EKC framework. Sustainability 16(2):474. https://doi.org/10.3390/su16020474
12. Barber BM, Jiang W, Morse A, Puri M, Tookes H, Werner IM (2021) What explains differences in finance research productivity during the pandemic?. J Finance 76(4):1655–1697
13. Barrios S, Görg H, Strobl E (2003) Explaining firms' export behaviour: Ramp;d, spillovers and the destination market*. Oxford Bull Econ & Stats 4:475–496. https://doi.org/10.1111/1468-0084.t01-1-00058
14. Becker GS (1993) Nobel lecture: the economic way of looking at behavior. J Polit Econ 101(3):385–409
15. Belloumi M, Alshehry A (2020) The impact of international trade on sustainable development in Saudi Arabia. Sustainability 13(12):5421. https://doi.org/10.3390/su12135421
16. Chudik A, Pesaran MH (2015) Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. J Econometrics 188(2):393–420
17. Dossani R, Kenney M (2007) The next wave of globalization: relocating service provision to India. World Dev 5(35):772–791. https://doi.org/10.1016/j.worlddev.2006.09.014
18. Dutta, S., Lanvin, B., León, L. R., & Wunsch-Vincent, S. (Eds.). (2021). Global innovation index 2021: tracking innovation through the covid-19 crisis. WIPO.
19. Dunning JH (1993) Multinational enterprises and the global economy. Addison-Wesley, Wokingham, England
20. Eberhardt M (2012) Estimating panel time-series models with heterogeneous slopes. Stata J 12(1):61–71
21. Eck K, Huber S (2016) Product sophistication and spillovers from foreign direct investment. Can J Econ. https://doi.org/10.1111/caje.12247
22. Eichenbaum MS, Rebelo S, Trabandt M (2022) The macroeconomics of testing and quarantining. J Econ Dyn Control 138:104337
23. Ellis P (2005) Market orientation and marketing practice in a developing economy. Eur J Mark. https://doi.org/10.1108/03090560510590746
24. Fakhrullah F, Xiao D, Suplata M et al (2025) Customer-centric value assessment of cryptocurrency adaptation. Comput Econ 66:4923–4958. https://doi.org/10.1007/s10614-025-10868-6
25. Fan P (2021) Export technological sophistication of China: measurement and impact factor. Discrete Dyn Nat Soc 2021:1–9
26. Gan S, Cheng D (2020) Exchange rate appreciation, R&d, and export sophistication: evidence from China. J Int Trade Econ Dev 29(2):237–246
27. Gereffi G (2020) What does the COVID-19 pandemic teach us about global value chains? The case of medical supplies. J Int Bus Policy 3:287–301
28. Goldberg P, Pavcnik N (2007) Distributional effects of globalization in developing countries. J Econ Lit 1(45):39–82. https://doi.org/10.1257/jel.45.1.39+
29. Heinzová R, Hoke E, Urbánek T, Taraba P (2023) Export and exports risks of small and medium enterprises during the COVID-19 pandemic. Probl Perspect Manage. https://doi.org/10.21511/ppm.21(1).2023.03
30. Im KS, Pesaran MH, Shin Y (2003) Testing for unit roots in heterogeneous panels. J Econometrics 115(1):53–74
31. Ishaq A, Sadaf M, Ali A, Naz S (2022) Imagining the growth in small and medium enterprises (SMEs) of Pakistan under COVID19 outbreak. iRASD J Econ 4(4):583–593
32. Jarreau J, Poncet S (2012) Export sophistication and economic growth: evidence from China. J Dev Econ 97(2):281–292
33. Kannen P (2020) Does foreign direct investment expand the capability set in the host economy? A sectoral analysis. World Econ 43(2):428–457
34. Karn, A., Karna, R. (2019). Supply line engineering on importation and exportation: Bimstec perspective.. https://doi.org/10.3846/cibmee.2019.016
35. Kato A (2022) Trade competition between ASEAN, China, and India: the post-trade war and COVID-19 scenario. Glob J Emerg Mark Econ 14(2):163–184
36. Khorana S, Martínez-Zarzoso I, Ali S (2023) An anatomy of the impact of COVID-19 on the global and intra-Commonwealth trade in goods. Rev Int Econ 31(2):550–579
37. Kočenda E, Poghosyan K (2018) Export sophistication: a dynamic panel data approach. Emerg Mark Finance Trade 54(12):2799–2814
38. Koopman R, Wang Z, Wei S (2012) Estimating domestic content in exports when processing trade is pervasive. J Dev Econ 1(99):178–189. https://doi.org/10.1016/j.jdeveco.2011.12.004
39. Lapatinas A, Kyriakou A, Garas A (2019) Taxation and economic sophistication: evidence from OECD countries. PLoS ONE 3(14):e0213498. https://doi.org/10.1371/journal.pone.0213498
40. Li J (2019) Export sophistication and outward FDI in developing countries. J Int Commer Econ Policy 10(03):1950017
41. Liu H, Wang X (2022) Spillover effects of foreign direct investment on export sophistication: evidence from Chinese domestic manufacturing firms. J Dev Stud 58(11):2393–2408
42. Liu X, Ornelas E, Shi H (2022) The trade impact of the Covid-19 pandemic. World Econ 45(12):3751–3779
43. Madonna M, Handoyo RD (2023) The effect of innovation, logistic performance, and human capital on export diversification of manufacturing industry. KINERJA 27(1):129–147
44. Mayneris F, Poncet S (2013) Chinese firms' entry to export markets: the role of foreign export spillovers. World Bank Econ Rev. https://doi.org/10.1093/wber/lht009
45. Mostafiz MI, Sambasivan M, Goh SK (2019) Measurement scale of international opportunity identification in early internationalization firms. Asia-Pacific J Business Admin 11(2):131–145
46. Mubarik M, Devadason E, Govindaraju C (2020) Human capital and export performance of small and medium enterprises in Pakistan. IJSE 5(47):643–662. https://doi.org/10.1108/ijse-03-2019-0198
47. Mukhtarov S, Alalawneh M, Ibadov E, Huseynli A (2019) The impact of foreign direct investment on exports in Jordan: an empirical analysis. J Int Stud. https://doi.org/10.14254/2071-8330.2019/12-3/4
48. Olubiyi E (2014) Trade, remittances and economic growth in Nigeria: any causal relationship? Afr Dev Rev. https://doi.org/10.1111/1467-8268.12081
49. Özsoy S, Fazlıoğlu B, Esen S (2021) Do fdi and patents drive sophistication of exports? A panel data approach. Prague Econ Pap 2(30):216–244. https://doi.org/10.18267/j.pep.755
50. Pesaran MH, Schuermann T, Weiner SM (2004) Modeling regional interdependencies using a global error-correcting macroeconometric model. J Bus Econ Stat 22(2):129–162
51. Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econometrics 22(2):265–312
52. Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. J Econometrics 142(1):50–93
53. Poghosyan, K., & Kočenda, E. (2016). Determinants of export sophistication: Evidence from Monte Carlo simulations (No. 360). IOS Working Papers.

54. Rahman MM, Alam K, Velayutham E (2022) Reduction of CO2 emissions: the role of renewable energy, technological innovation and export quality. Energy Rep 8:2793–2805
55. Rehman FU, Sohag K, Saeed T (2023) Impact of sectoral infrastructure on export and foreign direct investment inflow: evidence from selected South Asian economies by applying a new global infrastructure index. J Infrastruct Syst 29(1):04022045
56. Rehman FU, Ding Y (2020) The nexus between outward foreign direct investment and export sophistication: new evidence from China. Appl Econ Lett 27(5):357–365
57. Romero, J. (2015). Exports, Imports, Fdi and Gdp In Mexico: 1989–2013. JEDS, 1(3). https://doi.org/10.15640/jeds.v3n1a8
58. Romer PM (1990) Endogenous technological change. J Polit Econ 98(5 Part 2):S71–S102
59. Sanjuan A, Dawson P (2010) Agricultural exports and economic growth in developing countries: a panel cointegration approach. J Agric Econ 3(61):565–583. https://doi.org/10.1111/j.1477-9552.2010.00257.x
60. Shirazi N, Manap T (2005) Export-led growth hypothesis: further econometric evidence from South Asia. Dev Econ. https://doi.org/10.1111/j.1746-1049.2005.tb00955.x
61. Song Y, Hao X, Zheng L (2022) Intermediate import, independent innovation and export sophistication of Chinese manufacturing enterprises. Struct Change Econ Dyn 60:126–140
62. Sousa C, Martínez-López F, Coelho F (2008) The determinants of export performance: a review of the research in the literature between 1998 and 2005. Int J Manag Rev 4(10):343–374. https://doi.org/10.1111/j.1468-2370.2008.00232.x
63. Tebaldi E (2011) The determinants of high-technology exports: a panel data analysis. Atl Econ J 4(39):343–353. https://doi.org/10.1007/s11293-011-9288-9
64. Vernon R (1966) International investment and international trade in the product cycle. Q J Econ 80(2):190–207
65. Wang H, Yang M, He R, Zheng P (2022) Environmental regulation, foreign direct investment, and export sophistication of China: an empirical study based on dynamic system GMM and threshold model. Environ Sci Pollut Res 29(48):72090–72100
66. Wang Q, Yang X, Li R (2023) Does intellectual property protection improve energy efficiency? Evidence from the impact of intellectual property income on energy intensity. Energy Environ. https://doi.org/10.1177/0958305x231180694
67. Wang, T., & Zhou, Q. (2022). Measurement of Export Sophistication of Various Regions in China and Analysis of Its Influencing Factors. In: Advances in Decision Science and Management: Proceedings of Third International Conference on Decision Science and Management (ICDSM 2021) (pp. 695–703). Springer Singapore.
68. Westerlund J (2007) Testing for error correction in panel data. Oxford Bull Econ Stat 69(6):709–748
69. Yan F, Li H, Wang W, Zhang J (2023) The trend in density of skilled health personnel in BRICS countries: implication for China and India. Health Planning & Management 3(38):759–772. https://doi.org/10.1002/hpm.3623
70. Zapata A, Arrazola M, Hevia J (2023) Determinants of high-tech exports: new evidence from OECD countries. J Knowl Econ. https://doi.org/10.1007/s13132-023-01116-z
71. Zhou C, Sun Z, Qi S, Li Y, Gao H (2023) Green credit guideline and enterprise export green-sophistication. J Environ Manage 336:117648

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