Title: The Impact of Frontier Technologies on Countries' Integration into Global Value Chains: Evidence from Panel Data Analysis of selected North African Economies (2008–2018)

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Abstract

This study examines the impact of frontier technologies on countries' integration into global value chains. A quantitative approach was adopted using panel data and a pooled ordinary least squares (OLS) model was applied to a sample of countries in North Africa over the period (2008–2018). The study used the Frontier Technology Readiness Index (FTRI) developed by the United Nations Conference on Trade and Development (UNCTAD), which consists of five main pillars: ICT diffusion, skills, research and development (R&D), industrial activity, access to finance, and the GVC participation index. The results indicate that ICT diffusion, access to finance, and skills have statistically significant positive effects on integration into global value chains. In contrast, R&D and industrial activity have statistically significant negative effects. This indicates that while some dimensions of frontier technology enhance countries' integration into global value chains, other dimensions may pose challenges, particularly in cases where local innovation systems or industrial structures are underdeveloped. The results underscore the importance of adopting a balanced approach that takes into account the context of frontier technology readiness to achieve effective integration.

Keywords: Frontier technologies, integration into global value chains, FTRI, GVC Participation Index.

Introduction

The technological changes and developments that have led to the emergence of leading technologies as one of the most important developments that affect the economic activity of countries and their position, and redefine competitive standards, and these technologies have become basic engines for the transformation in global production patterns. To refuse from the core of this transformation the concept of global value chains, which depends on cross -border coordination, by converting raw materials into parts and components, then collecting final products and connecting them to the final consumer, as well as effective publishing technology, flowing information to improve production, reducing costs, and enhancing value creation.

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The leading technologies have the ability to improve the ability of countries significantly to integrate into global value chains and upgrade them by increasing productivity, empowering specialization, and facilitating digital trade. However, the integration of these technologies into national strategies and corporate strategies puts a set of challenges, including disparities in digital infrastructure, inequality in obtaining financing, gaps in human capital, and the variation of research and development capabilities. Consequently, the potential capacity or the great future capabilities that these leading technologies are expected to achieve with strategic investments in institutional readiness, skills development, and innovation systems and support policies.

Research Problem

Despite the increasing recognition of the transformational force of leading technologies, their integration into strategies aimed at enhancing integration into global value chains remains different between countries, so the main question is: To what extent do the leading technologies affect the ability of countries to integrate into global value chains?

Stady Hypothesis

H1: Access to finance deployment has a statistically significant effect on Integration into Global Value Chains;

H2: Information and Communications Technology (ICT) deployment has a statistically significant effect on Integration into Global Value Chains;

H3: Industry activity deployment has a statistically significant effect on Integration into Global Value Chains;

H4: Research and Development (R&D) activity deployment has a statistically significant effect on Integration into Global Value Chains;

H4: Skills –Using deployment has a statistically significant effect on Integration into Global Value Chains.

Theoretical Framework for the Study

1. Frontier technologies

The "frontier technologies" are a group of new technologies that take advantage of digitalization and connectivity which enable them to combine to multiply their impacts. These technologies can have dramatic impacts on economies and societies as well as on the development of other technologies. Which covers artificial intelligence (AI), the Internet of Things (IoT), big data, blockchain, 5G, 3D printing, robotics, drones, gene editing, nanotechnology, and solar photovoltaic. (UNCTAD, 2021, p. 18)

Table 1. Frontier technologies

Technology	Description
Artificial intelligence (AI)	AI is normally defined as the capability of a machine to engage in cognitive activities typically performed by the human brain. AI implementations that focus on narrow tasks are widely adopted today, used for example, in recommending what to buy next online, for virtual assistants in smartphones, and for spotting spam or detecting credit card fraud. New implementations of AI are based on machine learning and harness big data.
Internet of Things (IoT)	IoT refers to myriad Internet-enabled physical devices that are collecting and sharing data. There is a vast number of potential applications. Typical fields include wearable devices, smart homes, healthcare, smart cities and industrial automation.
Big data	Big data refers to datasets whose size or type is beyond the ability of traditional database structures to capture, manage and process. Computers can thus tap into data that has traditionally been inaccessible or unusable.

Blockchain	A blockchain refers to an immutable time-stamped series of data records supervised by a cluster of computers not owned by any single entity. Blockchain serves as the base technology for cryptocurrencies, enabling peer-to-peer transactions that are open, secure and fast.
5G	5G networks are the next generation of mobile internet connectivity, offering download speeds of around 1–10 Gbps (4G is around 100 Mbps) as well as more reliable connections on smartphones and other devices.
3D printing	3D printing, also known as additive manufacturing, produces three-dimensional objects based on a digital file. 3D printing can create complex objects using less material than traditional manufacturing.
Robotics	Robots are programmable machines that can carry out actions and interact with the environment via sensors and actuators either autonomously or semi-autonomously. They can take many forms: disaster response robots, consumer robots, industrial robots, military/security robots and autonomous vehicles.
Drones	A drone, also known as unmanned aerial vehicle (UAV) or unmanned aircraft systems (UAS), is a flying robot that can be remotely controlled or fly autonomously using software with sensors and GPS. Drones have often been used for military purposes, but they also have civilian uses such as in videography, agriculture and in delivery services.
Gene editing	Gene editing, also known as genome editing, is a genetic engineering tool used to insert, delete or modify the genome in organisms. Potential applications include producing drought-tolerant crops or new antibiotics.
Nanotechnology	Nanotechnology is a field of applied science and technology dealing with the manufacturing of objects in scales smaller than 1 micrometre. Nanotechnology is used to produce a wide range of useful products such as pharmaceuticals, commercial polymers and protective coatings. It can also be used to design computer chip layouts.
Solar photovoltaic (Solar PV)	Solar photovoltaic (Solar PV) technology transforms sunlight into direct current electricity using solar converters within PV cells. In addition to being a renewable energy technology, solar PV can be used in off-grid energy systems, potentially achieving electricity cost and increasing access.

Source : (UNCTAD, 2021, p. 17)

2. Readiness Index for Frontier Technology Adoption

There are challenges in establishing a clear and unified definition of frontier technology, leading to differences in how it is measured and represented in different studies. Although there is no consensus on a single indicator to measure it, based on the nature of the current study, the Frontier Technology Readiness Index will be chosen to measure frontier technology, as defined by The United Nations Conference on Trade and Development (UNCTAD): "The Frontier Technology Readiness Index covers 158 countries worldwide and is intended to assess the extent to which countries are prepared for, able to use, adopt, and adapt frontier technologies in a fair and inclusive manner." (UNCTAD, Technology and Innovation Report 2021, 2021, p. 10)

The Frontier Technology Readiness Index developed by UNCTAD presents data covering technological capabilities related to physical investment, human capital, and technological effort. It assesses countries' national capacities to **use**, **adopt**, and **adapt** these technologies as follows: (UNCTAD, Technology and Innovation Report 2021, 2021, pp. 144-145)

- **Use**: This requires basic capabilities, passive skills (non-innovative use), effort, infrastructure, and some technological awareness. For example, it could involve following an AI-driven recommendation from an e-commerce website or using a chatbot.

- **Adoption:** Active use for specific purposes demands more advanced capabilities. This might involve using AI to generate recommendations or deploying a chatbot on a commercial website.
- **Adaptation:** Modifying technologies requires even more advanced capabilities, such as designing AI-based recommendation systems or localizing chatbot features.

3. Pillars and Sub-Indicators of the Readiness Index for Frontier Technology Adoption

Based on a review of the literature, UNCTAD's analytical and technical cooperation work, consultations with internal and external experts, and data availability, five key pillars were selected to build the index and assess countries' abilities to use, adopt, and adapt frontier technologies: (UNCTAD, Technology and Innovation Report 2021, 2021, pp. 144-145) (UNCTAD stat, 2025)

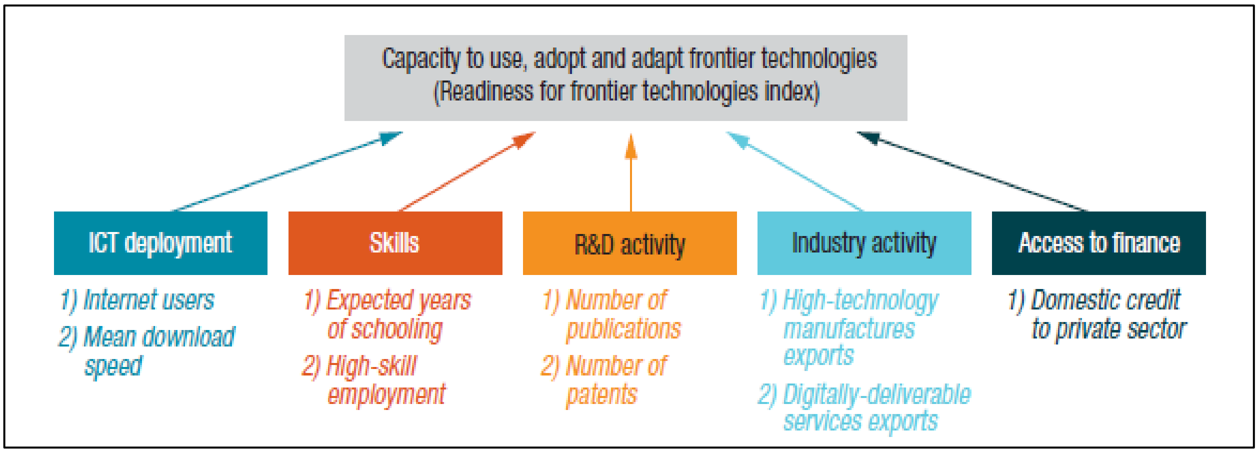


Fig 1. Structure of the readiness index

Source: (UNCTAD, 2021, p. 22)

3.1. Access to Finance: This pillar assesses the availability of financing for the private sector, as improving access to finance can accelerate the use, adoption, and adaptation of frontier technologies. To measure this, the following sub-indicator is used: (UNCTAD stat, 2025)

➢ **Domestic Credit to the Private Sector:** Expressed as a percentage of GDP, this indicator captures resources provided by financial institutions (such as leasing companies, money lenders, insurance companies, pension funds, and foreign exchange firms). It includes various financial instruments such as loans, non-equity securities, trade credits, and other receivables.

However, alternative or non-traditional financing providers or financial instruments may not be fully captured by this indicator.

3.2. ICT Deployment: This pillar examines the state of ICT infrastructure. Using, adopting, and adapting frontier technologies requires robust ICT infrastructure, especially since technologies like AI, IoT, Big Data, and blockchain are internet-based. Two key aspects of infrastructure are considered: *Availability*, ensuring inclusive access for all, and *Quality*, enabling more effective and advanced use The following sub-indicators are used to assess ICT deployment:

➢ **Internet Users:** The percentage of the population using the internet, reflecting internet infrastructure penetration.

➢ **Average Download Speed:** Measured in megabits per second (Mbps), assessing internet connection quality.

3.3. Industrial Activity: This pillar measures the capacity of local industries to produce frontier technologies and export digital services. It assesses the industrial capabilities of a country to use, adopt, and adapt frontier technologies, using the following sub-indicators: (UNCTAD stat, 2025)

- **High-tech Exports**: The percentage of total merchandise exports comprised of high-tech industry exports.
- **Digitally Deliverable Services Exports**: The percentage of total service exports represented by digital services. (unctadstat, 2023)

3.4. Research and Development Activity (R&D): R&D is essential not only for producing frontier technologies but also for adopting and adapting them, as these often require localization or customization. This pillar assesses a country's ability to tailor technology to local needs using the following sub-indicators: (UNCTAD stat, 2025)

- **Scientific Publications**: The number of publications related to frontier technologies in a given country.
- **Patents**: The number of patent filings related to frontier technologies in a given country.

It should be noted that informal R&D activities, especially in developing countries, may not result in publications or patents, and thus actual R&D levels might be underrepresented.

3.5. Skills: Utilizing, adopting, and adapting frontier technologies require individuals equipped with appropriate and relevant skills. While some of these skills may be advanced, they are generally less than those needed to invent frontier technologies. Skills can be acquired through: *Education, and Workplace training or learning-by-doing*. This pillar is assessed through the following sub-indicators: (UNCTAD stat, 2025)

- **Educational Attainment**: Measured by the expected number of years of schooling in the population.
- **Workplace Skills**: Measured by the share of the employed population in high-skilled occupations, defined by the International Labour Organization (ILO) to include managers, professionals, technicians, and associate professionals, based on the International Standard Classification of Occupations.

Note: These indicators must be interpreted cautiously, especially in developing countries, due to brain drain or emigration of highly skilled individuals, which may result in lower actual skills levels than official figures suggest. (UNCTAD stat, 2025)

4. Integration into global value chains

Integration into global value chains: It is "a chain of stages that constitute the process of producing a good or providing a service intended for sale to consumers. Each of these stages contributes to increasing the value of the product, and at least two of these stages must take place in two different countries." (World Bank;, 2020, p. 17) In this context, Integration into global value chains refers to a multifaceted process whereby countries and companies participate in cross-border production stages. The aim is sustained engagement with global value chains-meeting ongoing international demand while securing their place within these global value chains. Countries contribute specific tasks aligned with their comparative advantage, adding value at each stage. This geographic distribution enhances efficiency, reduces costs, and improves product quality by leveraging each country's unique expertise and resources.

5. Global Value Chain Participation Index

Global Value Chain Participation Index: "An indicator that measures the extent to which countries are integrated into global production networks and their contribution to value creation within specific industries. It can be calculated using the sum of foreign value added (FVA) and indirect domestic value added (DVX) divided by total exports." (EBRD, 2020, p. 6). The index reflects countries' participation in global value chains and their integration into the production and trade of goods and services across international borders.

Methods for assessing participation in global value chains have witnessed significant developments, and various indicators, such as the ratio of imported inputs to GDP, to total inputs, or to exports, have been adopted to determine countries' participation in these chains (Haltmaier, 2015, p. 5) However, Hummels, Ishei, and Yi (2001) and Chen et al. (2005) argue that these indicators may not be entirely accurate, as they do not accurately measure the use of imported intermediate goods in exports compared to their use in domestic production (Aslam, Natalija , & Rodrigues-Bastos, 2017, p. 16). Then, Hummels, Ishei, and Yi (2001) and Chen et al (2005) introduced the vertical specialization measures (VS, VS1) (Nenci, 2020, p. 7) to calculate the overall bilateral participation index in global value chains by combining the two indicators (VS, VS1), as this index measures the overall bilateral participation in the chains from one country to another (De

Backer & Miroudot, 2013, p. 5) (Borin & Mancini, 2019, p. 20) (Nenci, 2020, p. 14). However, the latter does not accurately reflect the extent of a country's participation in these chains, as it calculates value added through (VS, VS1), which is limited to only two countries. That is, the index does not accurately divide exports into foreign and domestic value-added components when the production chain extends to several countries (Haltmaier, 2015, pp. 6-7). Therefore, Koopman et al. (2010 and 2014) proposed a method to analyze total exports into (DVA) domestic value added and (FVA) foreign value added. Based on the work of Hummels et al. (2001) and Johnson & Noguera (2012),... (Aslam, Natalija , & Rodrigues-Bastos, 2017, p. 17), and by using elements of the Koopman et al. method, the Global Value Chain Participation Index was developed (Foster-McGregor, Kaulich, & Stehrer, 2015) to measure participation in global value chains, as this index takes into account the transit of intermediate goods. It crosses country borders multiple times, meaning it measures the added value that more than two countries contribute to the production process (Zenasni & Jaafari, 2021, p. 368).

The Relationship between Frontier Technology and Integration into Global Value Chains

There is a scarcity of studies examining the direct link between frontier technology and integration into global value chains, according to the sources reviewed. However, this relationship is evident across the sub-indices of the Frontier Technology Readiness Index, which measures frontier technology and integration into global value chains.

Studies by (APEC, 2016) (García-Alcaraz, Maldonado, Alor-Hernández, & Sanchez-Ramirez, 2017), and (Dehgani & Navimipour, 2019) have shown that digital infrastructure, including ICT and broadband, plays a vital role in facilitating seamless communications and data exchange, which is essential for coordinating global production activities. This infrastructure supports e-commerce and digital commerce, meets the operational needs of businesses, provides advanced environments for technological innovation, and fosters Frontier technologies, enhancing companies' competitiveness and integrating them into global markets and value chains.

(Mudambi, 2008), (Collins, Worthington, Reyes, & Romero, 2010), and (McDermott & Pietrobelli, 2017) mentioned that improving workforce skills through specialized educational and training programs, facilitated by partnerships between industry, universities, research centers, and others, helps employees acquire advanced skills and enable them to use modern technology efficiently. This leads to increased employment opportunities and the availability of highly skilled workers in high-tech fields. This trained workforce contributes to enhancing companies' ability to develop superior technologies and improve the quality of existing products. As a result, companies become more competitive in global markets, enhancing their integration into international value chains and increasing their attractiveness in global markets. In studies conducted by (Khan & Chaudhry, 2019), (Habib & Abbas, 2019), (Yang & Yi, 2021), (Zhang , Mohsin, Rasheed, Chang , & Taghizadeh-Hesary, 2021), (Tradi, Brock, & Kvilhaug, 2023), investing in human capital, such as education, work experience, and training, can have two aspects. First, investing in education and higher education as part of human capital enhances individuals' ability to contribute to research and development activities, indirectly contributing to economic growth by promoting technological innovation and creating opportunities for integration into global value chains. Second, investing in work experience and technical and vocational training enhances labor capabilities and improves their productivity, leading to increased economic growth. This is achieved by improving workers' skills and their ability to innovate, which enhances productivity and the ability to meet global standards, thus accessing markets and integrating into global value chains.

According to studies by (Khan & Chaudhry, 2019), (Habib & Abbas, 2019), (Yang & Yi, 2021), (Zhang , Mohsin, Rasheed, Chang , & Taghizadeh-Hesary, 2021), (Tradi, Brock, & Kvilhaug, 2023) Investment or spending on research and development (R&D) has a positive impact on integration into global value chains. R&D directly contributes to technological innovation and the development of Frontier technologies, which enhances countries' competitiveness in global markets. Therefore, investment in R&D can lead to the discovery of new technologies that stimulate economic growth by creating new industries and improving efficiency in existing industries. This can increase economic growth and global competitiveness, enhance integration into global value chains, and move up through them through improved technological and productive capabilities. While R&D is often viewed as critical to the use, adoption, and adaptation of leading technologies, numerous studies, such as (Shin, Kraemer , & Dedrick, 2009), (KWON & PARK, 2013), (Barasa, Kimuyu, Kinyanjui, Vermeulen , & Knoben, 2015), (Douglas & Ramirez, 2023), (Furusawa & Ishida, 2024), confirm that it has a negative and restrictive impact on integration into global value chains. This is particularly true in the absence of strong absorptive capacity or supportive governance, or due to conflicts between the centralization of multinational corporations and the local innovation needs of subsidiaries. These include the dominance of leading technologies by leading firms, which restricts knowledge flows and intellectual property development, and weak technical efficiency due to internal R&D, especially when not coupled with competent human capital.

Most of researchers (Hiranya & Lirong , 2017), (Mon & Del Giorgio, 2021), (Bettiol & Capestro, 2021), and (Sikka, Alok Sarkar, Sarkar, & Garg, 2022) proved the adoption of creative outputs, including various intangible assets, creative services, and online services such as information and communications technology (ICT) and Industry 4.0 outputs, impact the improvement of local industries in terms of operations, efficiency, productivity quality, and operating costs. This enables companies to leverage advanced technologies to achieve a competitive advantage, thereby producing Frontier technologies. This facilitates access to new markets, makes them more interconnected and responsive within the global market, and thus qualifies them for integration into global value chains, upgrading them, and making them more sustainable. Similarly (Yang & Yi, 2021) indicated in their study that companies should focus on using intangible assets such as creative outputs to create creative goods and services (cultural services, national films, the media and entertainment market, creative goods, etc.), contributing to creative exports (exports of digitally deliverable services) as part of overall trade, and thus integrating into global value chains. However, some studies, (Pu, Yee, Chong, Cai, & Lim, 2019), (Götz & Jankowska, 2020), (Larson, 2021), (Dvořáková, et al., 2021), have shown that reliance on traditional industrial activity without technical and professional modernization may hinder the adoption of modern technology and weaken integration into global value chains, especially in sectors or countries that lack policies that support digital transformation and training. This is due to overreliance on labor-intensive industries (such as low-tech manufacturing) and the lack of flexibility in industrial structures, which leads to resistance to change and slows down technological adoption, making countries less able to use, adopt, and adapt leading technology. Furthermore, weak training and technical education in various industries leads to a weak ability to adopt leading technology, which creates a digital divide and hinders effective integration into global value chains.

Several studies (Schmukler & Vesperoni, 2000), (Manova & Yu, 2014), (Lin & Qiao, 2020) have highlighted the importance of access to finance and credit facilities, i.e., the availability of finance for companies and the resources provided by financial companies to integrate into global value chains. These researchers emphasize that companies that enjoy better financing terms, whether through local or international markets, have greater opportunities to integrate into global value chains. This is achieved by improving financing terms, such as debt maturity and access to international capital markets, which facilitates these companies' expansion and increases their competitiveness in global markets.

Data Sources

This study relied on statistical data from the Frontier Technology Readiness Index (FTRI) and the Global Value Chain Participation Index (GVC Participation Index). The FTRI was developed by UNCTAD Statistics (2025) (UNCTAD stat, 2025), which includes globally collected data on information and communication technology (ICT) diffusion, skills, research and development (R&D), industry capabilities, and access to finance. The data used to calculate the GVC Index were also obtained from the UNCTAD-EORA Global Value Chain Database (GVC). According to the source (worldmrio, 2025), the UNCTAD-EORA Global Value Chain Database provides comprehensive global coverage, covering 189 countries and territories (including the "Rest of the World" aggregate), and provides a consistent time series spanning the period from 1990 to 2018. The database includes key GVC indicators, such as foreign value added (FVA), domestic value added (DVA), and indirect value added (DVX). It should be noted that no updated data is available in the database after 2018.

Panel data regression results

To provide empirical insights into the impact of frontier technologies on countries' integration into global value chains, panel data were used for a group of countries in the North Africa region (Algeria, Egypt, Mauritania, Morocco, Sudan, and Tunisia) from 2008–2018. Following are the regression equations:

$$\begin{aligned} \boldsymbol{GVC\ participation}_{it} &= \boldsymbol{\beta_0} + \boldsymbol{\beta_1 ACCESS\ TO\ FINANCE}_{it} + \boldsymbol{\beta_2 ICT}_{it} + \boldsymbol{\beta_3 INDUSTRY\ ACTIVITY}_{it} \\ &+ \boldsymbol{\beta_4 RESEARCH\ AND\ DEVELOPMENT}_{it} + \boldsymbol{\beta_5 SKILLS}_{it} + \boldsymbol{\varepsilon}_{it} \end{aligned}$$

The above equation, β_0 represents the constant term, while β_1, β_2, β_3, β_4, and β_5 correspond to the coefficients of the variables. The term ε_{i} denotes the residual error of the regression. All estimations were carried out using the EVIEWS software along with standard calculation methods.

To estimate the specified model and examine the relationships among the variables The Pooled ordinary least square (OLS) model is used to investigate the relationship between the dependent variable and the independent variables.

Test of multicollinearity

Multicollinearity refers to the existence linear relationship among the explanatory variables. (Jakpar , Tinggi , Kah hui , Johari , & Myint , 2019)

Table 2. multicollinearity Test

variables	VIF	Tolerance (1/VIF)
access_to_finance	3.306389	0.302445
ict	4.092171	0.244369
industry_activity	3.578726	0.279429
research_and_development	5.220873	0.191539
skills	3.644273	0.274403
mean vif	3.9684864	

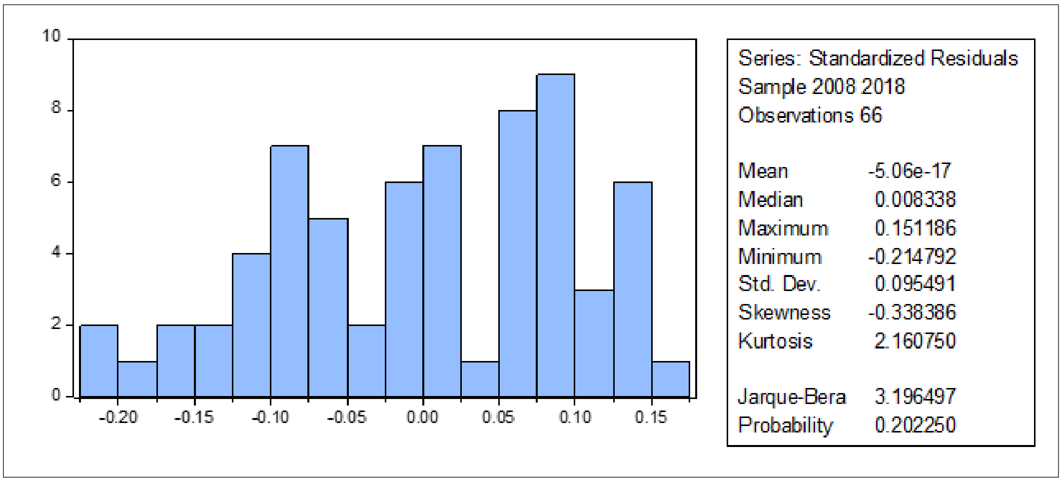
Source: **Author's calculation through EVIEWS software.**

The results above show that the value of VIF is less than ten (<10), thus, it is safe to say that there is multicollinearity between the independent variables in the model.

Normality Test

For testing the assumptions of regression model, firstly, normality of the models was checked Figure 2 shows the normality histogram along with some statistics that indicate the normal distribution of the error terms.

Figure 2. Tests *of normality.*



***Source*:** **Author's calculation through EVIEWS software.**

The Jarque–Bera test yields a p-value of 0.202250, which is well above the conventional 0.05 threshold. Taken together, these indicators confirm that the data is normal and ready for the next analysis test.

Test of heteroscedasticity

Heteroskedasticity arises when the variance of the error term, given the independent variables, is not constant. It frequently accompanies other assumption violations. The Breusch–Pagan–Godfrey test assesses this by testing the null hypothesis of homoscedasticity against the alternative of heteroskedasticity. (Heriat, Nid, & Abdelli, 2025)

Table 3. *Test of Heteroscedasticity.*

Test	*Chi-squared (χ2)*	*Prob > chi²*
Breusch-Pagan LM	*36.49055*	*0.0715*

Source: **Author's calculation through EVIEWS software**

the p-value of the heteroscedasticity test is smaller than 0.05 (5% significance level), it is statistically significance at 5% significance level. Hence, reject the null hypothesis. Therefore, it means there is heteroscedasticity problem in the proposed Pooled-Effect Model.

Autocorrelation Test

Autocorrelation means that there is no correlation between one each observation regarding the time frame of the analysis. To detect autocorrelation, we need to measure Durbin-Watson (DW) method. (Yusuf & Dai, 2020, p. 12)

Table 4. Autocorrelation test.

Metric	*Value*	*Metric*	*Value*
R-squared	*0.608561*	*Mean dependent var*	*0.544981*
Adjusted R-squared	*0.559274*	*S.D. dependent var*	*0.124167*
S.E. of regression	*0.099390*	*Akaike info criterion*	*-1.693022*
Sum squared resid	*0.592703*	*Schwarz criterion*	*-1.493962*
Log likelihood	*61.86973*	*Hannan-Quinn criter.*	*-1.614364*
F-statistic	*8.289494*	*Durbin-Watson stat*	*0.287566*
Prob(F-statistic)	*0.000005*		

Source: **Author's calculation through EVIEWS software.**

Based on Table 4, the Durbin–Watson statistic is 0.287566, which is well below 2 and therefore indicates strong positive autocorrelation in the residual meaning consecutive errors tend to share the same sign.

Discussions

After conducting the necessary statistical tests and analyzing them, the following results were reached:

Table 5. *pooled Effect regression.*

Variable	Coefficient	Prob
ACCESS_TO_FINANCE	*0.311058*	*0.0282*
ICT	*0.343372*	*0.0282*
INDUSTRY_ACTIVITY	*-0.368940*	*0.0051*
RESEARCH_AND_DEVELOPMENT	*-0.771134*	*0.0019*
SKILLS	*0.625242*	*0.0000*
C	*0.376460*	*0.0000*

Source: **Author's calculation through EVIEWS software.**

Based on the results of the Pooled effect model in Table 5, we find that:

1- The coefficient for ACCESS TO FINANCE is 0.311058, with a probability value of 0.0282. Since the p-value is less than 0.05, this suggests that access to finance has a statistically significant effect on GVC participation at the 5% significance level. This finding supports Hypothesis H1 and is consistent with the empirical evidence reported in prior studies by (Schmukler & Vesperoni, 2000), (Manova & Yu, 2014), (Lin & Qiao, 2020)

2- The Coefficient for ICT is 0.343372 with a probability value of 0.0282. since the p-value<0.05. this indicates that ICT has a statistically significant positive effect on GVC participation. Accordingly, this finding validates Hypothesis H2, and aligns with the outcomes in earlier empirical research (APEC, 2016) (García-Alcaraz, Maldonado, Alor-Hernández, & Sanchez-Ramirez, 2017), and (Dehgani & Navimipour, 2019)

3- The estimated coefficient for INDUSTRY ACTIVITY is -0.368940, accompanied by a probability value of 0.0051. Although statistically significant at the 5% level, the negative sign contrasts with the expected positive relationship. As such, the result does not support Hypothesis H3 It is consistent with the results in previous experimental literature. (Pu, Yee, Chong, Cai, & Lim, 2019), (Götz & Jankowska, 2020), (Larson, 2021), (Dvořáková, et al., 2021)

4- The Coefficient for RESEARCH AND DEVELOPMENT is -0.771134 with a probability value of 0.0019. since the p-value>0.05. this indicates that RESEARCH AND DEVELOPMENT has a statistically significant negative effect on GVC participation. The result is not in line with the H4 hypothesis, but aligns with the previous research cited. (Shin, Kraemer , & Dedrick, 2009), (KWON & PARK, 2013), (Barasa, Kimuyu, Kinyanjui, Vermeulen , & Knoben, 2015), (Douglas & Ramirez, 2023), (Furusawa & Ishida, 2024)

5- The coefficient associated with SKILLS is 0.625242, with a probability value of 0.0000, indicating a statistically significant impact on GVC participation at the 5% level. This outcome provides strong empirical support for Hypothesis H1 and corresponds with the patterns observed in earlier studies addressing the role of human capital in global value chain integration (Mudambi, 2008), (Collins, Worthington, Reyes, & Romero, 2010), and (McDermott & Pietrobelli, 2017), (Khan & Chaudhry, 2019), (Habib & Abbas, 2019), (Yang & Yi, 2021), (Zhang , Mohsin, Rasheed, Chang , & Taghizadeh-Hesary, 2021), (Tradi, Brock, & Kvilhaug, 2023)

Conclusion

The current study provides empirical insights into how the diffusion of frontier technologies (artificial intelligence (AI), the Internet of Things (IoT), big data, blockchain, 5G, 3D printing, robotics, drones, gene editing, nanotechnology, and solar photovoltaic) contributes to integration into global value chains and the conditions necessary to unleash their full potential. The findings suggest that frontier technologies should not be viewed merely as enabling tools, but rather as strategic tools for economic upgrading and deepening integration into global value chains. Governments, businesses, and international organizations must work together to harness their transformative power, mitigate associated risks, and ensure that the benefits of using, adopting, and adapting frontier technologies are fairly distributed.

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