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The Moderating Role of Human Capital on the Relationship Between Globalization and Green Technology Adoption in Emerging Economies

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Abstract

Shifting to clean energy technologies is important for emerging economies that aim to separate economic growth from environmental harm. Existing literature shows that globalization channels promote the adoption of green technology; however, a significant gap remains in understanding how local human capital influences this international spillover. Using annual data of 25 emerging economies from 2000 to 2021, we examine whether local human capital moderates the impact of globalization's dimensions on the adoption of green technology across emerging economies, using a two-step System GMM methodology. We find that economic, social, and trade globalization cannot alone affect the adoption of green technology, whereas financial globalization does so directly. But their interaction with local human capital has a robust and significant impact on the adoption of green technology. The empirical results suggest that if there are no skilled technicians or engineers, imported technologies will remain underused or unused in warehouses, empirically suggesting that the adoption of green technology through globalization relies heavily on a skilled workforce to implement this transition. On this result, we offer a few policy suggestions to governments in emerging economies: enhance investment in advanced technology, STEM education, mandatory corporate green training contracts and upskilling the workforce.

Keywords: Green Technology Adoption, Globalization, Human Capital, Absorptive Capacity, System GMM, Emerging Economies.

JEL Classification : F64 , J24 ,O13,O33,Q55

1 Introduction

Emerging market economies are facing a difficult situation in the global development landscape right now. On the one hand, they face internal pressure to maintain higher economic growth to address socio-ecological problems such as poverty, inequality, and infrastructure development, and to enhance the standard of living for the growing population. Moreover, emerging economies have unique demographic challenges and rapid urbanization that put pressure on them to provide employment opportunities and basic social services. On the other hand, this economic growth has negative side effects that transcend local borders and will have an impact at the global level: global environmental issues such as rising temperatures, rising sea levels, forced climate migration, and the loss of millions of species (Abbass et al., 2022). These emerging nations are caught in a giant trap, as the only way to bring even a little progress on socio-ecological issues is by harming the global environment through negative externalities like pollution. Even a major emerging economy like China, which has experienced rapid growth in manufacturing and global trade over recent decades, has suffered significant negative impacts from this development due to its heavy reliance on fossil fuels to fulfill rising energy needs. (Economy, 2013). This encompasses rising CO_2 emissions, deteriorating air and water quality, and excessive use of natural resources (Erumban et al., 2019). Thus, rapidly growing environmental issues require an urgent move towards cleaner production methods and sustainable development.

The rise of global environmental challenges is linked to twin pressures on the economy in emerging economies over the past few decades, namely structural transformation (industrialization) and rising global integration. However, industrialization is an important part of economic growth in emerging economies (Lewis, 2013; Ranis & Fei, 1961). The existing literature confirms that as industrialization increases in emerging economies, there is a structural shift from agriculture to industry. Because the industry relies on heavy machinery and plants, energy demand increases. This increase in energy demand is largely met by non-renewable sources such as fossil fuels (Sadorsky, 2014), and non-renewable energy is the primary driver of environmental degradation. (Khan et al., 2023). Furthermore, the rapid pace of global integration has been responsible for the rise in global demand for products and services, creating a parallel need for more power. Global integration is highly dependent on energy demand, largely met by non-renewable sources, which worsens environmental degradation (Shahbaz et al., 2017a). Furthermore, trade liberalization often leads to increased pollution in emerging economies by shifting pollution-intensive production to regions with lax environmental laws. (Onwachukwu et al., 2021). This situation is known as the 'pollution haven hypothesis,' which means that global trade may have a negative effect on the emerging nations by making them manufacturing centers for carbon-intensive products used by advanced nations.

To address these worldwide environmental risks, member countries made a legally binding international treaty at the Paris UN Climate Conference (COP21). The treaty made it mandatory to limit the global temperature increase to below 2°C above the pre-industrial era, with an aspirational goal of keeping it under 1.5°C. To meet these targets, countries must create national strategies to tackle these environmental challenges. (UNFCCC, 2015). In this context, shifting toward clean energy has emerged as a key solution to decouple economic growth from environmental degradation. Existing research shows that advanced economies, such as the OECD, the USA, and the EU, have reduced environmental degradation through the use of clean energy (Özkan et al., 2023; Hou et al., 2023). However, for emerging economies, transformation is challenging due to carbon lock-in and high technology costs. The advanced economies have a mature financial capital market and research labs, whereas the emerging economies are always short of financial resources and also face the issue of path dependence on fossil fuel infrastructure, making it difficult for them to make a transition to a green economy.

On the other hand, globalization offers a pathway for emerging economies to overcome these domestic challenges. Through multidimensional pathways of globalization, such as global value chains, FDI, trade openness, and cultural exchanges, developing countries gain the vital ability to import advanced clean technologies from wealthier nations (Elfaki & Ahmed, 2024; Bilal et al., 2022). However, simply having environmental technologies available is not enough to guarantee their domestic adoption. As Cohen & Levinthal (1990) highlight, a country's internal absorptive capacity—determined by the depth and scale of its human capital—is a critical piece of the puzzle. If the nation lacks the necessary human resources to install, repair, and maintain the technology and adapt it to local needs, the technology will either be underused or left idle in government-funded warehouses. Hence , the adoption of green technology in any economy is also largely dependent upon scientific and technical literacy of domestic human capital.

This study has added to the existing research in two important ways: (1) it focuses on Green Technology. Adoption at the national level, while earlier works have touched on the diffusion or infusion of green technology, is one of the key results of globalization.(2) It presents econometric evidence that human capital acts as a buffer between globalization and the adoption of green technology

The remaining sections of this paper are organized as follows. Section 2 provides a review of the pertinent theoretical literature. Section 3 introduces existing theoretical literature. Section 4 details the data sources and the econometric methodology employed. Section 5 presents and elucidates the empirical results. Finally, Section 6 concludes with an overview of policy implications.

2 Literature Review

Globalization is a multidimensional phenomenon encompassing the expansion of trade, the liberalization of financial markets, the sharing of knowledge and technology, and the signing of international treaties to address both global and local issues (Gygli et al., 2019). It affects people's lives in many ways and is difficult to define narrowly because it spans economic, social, political, and cultural domains (Bodisla et al., 2017). The process has become increasingly important in emerging economies due to rising trade, foreign direct investment (FDI), and cultural and knowledge sharing. Globalization involves the dissemination of knowledge and the expansion of advanced technologies and ideas. technologies and manufacturing processes, thereby encouraging the adoption of cleaner, greener technologies (Verma et al., 2025). It also promotes better trade policies that lower trade barriers and supports green technologies (Bilal et al., 2021). Scholars such as Fu et al. (2025) and Xu (2024) have emphasized that globalization accelerates the adoption of green technologies. The current literature indicates that the policy goal should be to increase globalization to promote knowledge transfer and encourage environmentally friendly innovation (Verma et al., 2025).

2.1 The Multi-dimensional Impact of Globalization on Green Technology

2.1.1 Impact of Economic Globalization

Globalization of the economy involves the increasing integration of global markets through the removal of trade and investment barriers. This promotes more trade and foreign investment (Chang & Lee, 2010). In the end, it makes countries more attractive to international investors. The literature holds two contrasting viewpoints regarding the impact of economic globalization on green technology uptake. First, they believe that economic globalization encourages the adoption of environmentally friendly technologies through three main channels. First, greater integration offers access to areas where advanced technologies are developed. This access reduces costs because these technologies can be imported via international trade (Garsous & Worack, 2022). Secondly, foreign direct investment (FDI) is a crucial element of economic development globalization. They are a means of transferring clean technology. Multinational companies in host countries tend to introduce eco-friendly technologies and processes, a phenomenon known as the 'Pollution Halo Hypothesis'. Third, countries with less trade restrictions or more trade liberalization tend to adopt environmental technologies earlier (Aydin et al., 2024). Likewise, it is clear that integrating digital technology, closely linked to economic globalization, supports faster and more sustainable economic growth in the Asia-Pacific region (Elfaki & Ahmed, 2024).

The second perspective suggests that foreign investors in the Philippines are more likely to introduce fewer clean technologies, which reduces the dissemination of green innovations (Abbass et al., 2022). Additionally, outward FDI in China (Luo et al., 2021) and long-term FDI in OECD countries (Behera & Sethi, 2022) have negatively affected green technology innovation.

2.1.2 Impact of Social Globalization

This part examines how global social change affects the adoption of green technology. Social globalization, defined as the worldwide exchange of culture, societal values, ideas, and knowledge, also increases demand for green innovations. Whereas economic globalization is largely market-driven, social globalization focuses on global consumer preferences and drives the adoption of sustainable technologies by individuals and companies (Fu et al., 2025). Researchers highlight those social interactions, such as peer influence, social trust, and societal pressures, play a crucial role in promoting technology adoption (Lio et al., 2025). Evidence shows that the social dimension of globalization has a greater influence on the uptake of renewable energy than the economic dimension (Nan et al., 2023). Furthermore, social globalization promotes eco-innovation, as demonstrated by the Driscoll-Kraay estimator model fitting analysis of G20 countries' data (Li et al., 2025). It also indirectly reduces energy intensity by disseminating environmental knowledge, technological skills, and sustainability principles globally (Maneejuk et al., 2026). Social globalization spreads eco-friendly ideas and attitudes through social media and the internet, thereby creating ecological awareness (Kirikkaleli & Adebayo, 2024). Therefore, sharing information and experiences through global social networks helps promote sustainable production and consumption practices (Kasap, 2026).

2.1.3 Impact of Trade Globalization

Trade liberalization, a foundational element of economic globalization, removes tariff barriers, allowing the easy movement of goods and services internationally and enabling emerging markets to adopt advanced technologies. Academics generally divide into two groups regarding their impact on eco-friendly technology. The first perspective argues that open trade policies strongly incentivize emerging economies to clean up their energy sectors. It enables the cheap import of green capital goods and renewable components. Research tracking Bangladesh, India, Pakistan, Sri Lanka, and Nepal confirms that trade openness directly enhanced their capacity to import solar panels, wind turbines, and related infrastructure (Murshed, 2018; Oh, 2024). Ultimately, trade globalization drives economic growth and introduces advanced technologies, which lead to the implementation of more rigorous environmental regulations (Onwachukwu et al., 2021).

However, under the second view, scholars such as Guo (2021) and Amankwah (2016) argue that trade liberalization can lead to the flow of old, unused technologies from advanced economies to emerging economies. This can worsen environmental damage in those countries. Moreover, G7 research indicates that higher trade liberalization correlates with reduced production costs as a result of greater competition from around the world, ultimately possibly causing a decrease in sustainable practices (Qi, 2024).

2.1.4 Impact of Financial Globalization

Financial globalization involves connecting domestic financial markets with worldwide capital markets. It enhances cross-border investment, banking and financialization. The section provides an overview of existing studies related to the effect of financial globalization on green technology adoption. The costs of clean-energy projects, including large-scale solar and wind, smart-grid systems, and energy-storage technologies, are significant. These costs are typically higher than the budgets of many emerging-economy governments or private sectors. International financial markets like green bonds, impact investing, and development finance institutions can help bridge this funding gap by attracting foreign investment into clean energy initiatives (Majeed et al., 2022; Adebayo et al., 2025). Financial globalization can foster clean energy innovation and spread, as it can overcome financing constraints that may prevent emerging economies from investing in green infrastructure on a large scale (Fatima and Safdar, 2025). Based on Asian economies, Xu et al. (2024) offer evidence that the combination of financial development, innovation and good governance is essential for a successful energy transition. In contrast to other aspects of globalization which tend to contribute to access to technology or to norms, financial globalization provides a direct supply of economic resources to convert this access into investment. This is a unique situation in which adoption would be possible without relying too much on other factors.

2.2 Human capital plays a crucial role in driving technological diffusion.

Human capital includes the knowledge, skills, and practices that allow individuals to earn income and profits for themselves, their employers, and society. The components of human capital also encompass basic literacy and arithmetic skills, as well as knowledge and skills that a person has acquired and in which they have special expertise (Kuzminov et al., 2019). Education and training contribute to human capital by making people more productive. This results in higher lifetime earnings, fewer days of unemployment, and better working conditions (Saiti & Chletsos, 2024). Existing panel data studies on human capital, especially green human capital in China's manufacturing sector, show that a knowledgeable and skilled workforce understands sustainable development principles. This understanding significantly enhances innovation in clean energy technologies and environmentally friendly practices. (Abbas & Najam, 2025). Similarly, Khan et al. (2026) and Mubarik & Naghavi (2022) demonstrate that human capital alone enhances environmental awareness and the demand for green energy, leading to increased innovation and adoption of green energy while supporting ecological mitigation (Khan et al., 2025). Economies aiming for sustainable development should encourage policymakers to focus on developing green human capital skills (Ni et al., 2025). Thus, a country's human capital plays a critical role in boosting clean energy adoption. Within the current research framework, multi-dimensional globalization and human capital are regarded as crucial factors influencing the adoption of green technology in both emerging and advanced economies. However, a significant gap exists in understanding how a country's domestic human capital affects the link between multidimensional globalization and green technology adoption. Specifically, current research has not explored how human capital interacts with globalization regarding green technology adoption. This suggests the need to explore how human capital influences the relationship between globalization and green technology adoption. Recognizing the importance of human capital, this research aims to determine whether it moderates the relationship between the dimensions of globalization and green technology adoption in emerging economies. The literature suggests that various forms of globalization have significantly increased the adoption of green technology. We expect that a country's human capital can enhance the connection between multidimensional globalization and green technology adoption.

This study, therefore, aims to explore the following hypothesis based upon different dimensions of globalization:

H1: The interaction between a country's human capital and economic globalization has a significantly positive effect on green technology adoption.

H2: Higher levels of national human capital positively condition the relationship between social globalization and the integration of clean technologies.

H3: Trade globalization requires a strong threshold of domestic human capital to optimally drive green technology adoption.

H4: The direct positive impact of financial integration on green technology adoption is further accelerated by domestic human capital assets.

3. Theoretical Model

3.1 Introduction

This chapter applies well-regarded theoretical perspectives to demonstrate that without an adequate level of local human capital, emerging nations cannot effectively adopt imported eco-friendly technologies. Although many economists view globalization as a primary driver of the spread of innovation and technology, this research shows that mere exposure to global markets is not enough. We contend that moving toward cleaner, greener technology heavily depends on the quality of domestic human resources. To substantiate this, we rely on three core frameworks: the Schumpeterian Frontier Opportunity (Aghion & Howitt, 1992, 1998), the Open-Economy Channels of Transmission (Grossman & Helpman, 1991), and the Augmented Theory of Absorptive Capacity (Nelson & Phelps, 1966; Benhabib & Spiegel, 1994). Using these theories, we support the development of the interaction term, which is the primary predicted outcome of this study interaction term $(GLOB_{it} \times HC_{it})$ which is the main predicted result from this study.

3.2 The Technological frontier and catch-up opportunities and Open Economy

This section employs the Schumpeterian Frontier Opportunity (Aghion & Howitt, 1992, 1998) and the Open-Economy Channels of Transmission (Grossman & Helpman, 1991) to examine how emerging economies reduce the existing technological gap via global integration.

According to Schumpeterian Frontier Opportunity theory, the worldwide technological level is represented by the Global Technological Frontier, while domestic technology lags behind it. Using Aghion and Howitt (199), represent the global technological frontier at time t as growing at a constant exogenous rate g, and let a_i denotes the technology frontier of an emerging economy *i*. The technological gap in an economy can be expressed as:

$$a_{it} = \frac{a_i}{A_t}$$

Where $a_{it} \in (0,1)$. As, a_{it} depicts the technological gap; a lower value signifies a wider technological gap, whereas a higher value indicates a narrower technological gap in the case of an emerging economy.

According to the convergence literature initiated by Gerschenkron (1962) and later formalized in modern Schumpeterian theory, this technological gap is actually described as a unique “advantage of backwardness." For economies at the frontier, achieving productivity growth requires genuine, resource-intensive innovation through R&D. In contrast, emerging economies with a low level of technological development mainly grow by imitating and adapting existing frontier technologies. Since copying or importing technology is much cheaper than developing new inventions, a larger technological gap theoretically offers greater potential for rapid catch-up growth through deeper integration with the world.

According to the Schumpeterian frontier model, catching up is not certain. The rate at which emerging economies catch up relies on their domestic conditions. There is a lot of non-rival knowledge at the global frontier, but the tacit and uncodified aspects of technology require a certain level of domestic capacity, often measured by institutions and human capital, for adoption. If the country is unable to adopt new technologies, the technology gap might create a vicious circle of lagging behind rather than moving forward. This reflects the value of human capital, which is discussed in the next section.

3.3 The Macroeconomic Level: Absorption Capacity Perspective and Human Capital's Moderating Role

Globalization is important in narrowing the technology gap for emerging economies, but the effectiveness of technology depends on local structural constraints such as human capital. This study confirms this relationship by drawing on Endogenous Growth and Technology Diffusion Theory (Nelson & Phelps, 1966; Benhabib & Spiegel, 1994) to account for countries' ability to absorb technology. Nelson and Phelps (1966) state that the concept of human capital is not only regarded as a production factor but also plays a significant role in the rate at which a country can adopt and utilize new technologies. Benhabib and Spiegel (1994) used this idea to develop an empirical model for comparing countries. They showed that the speed at which a country adopts a new technology depends on two main factors: local human capital and global integration. Clean technologies are advanced technologies that will not simply function if a country imports them. They also need skilled human capital with sufficient knowledge to perform installation, operation, and repair.

This can be further explained through two scenarios :

(1) Low Human Capital: If a country opens its border, then the imported advanced clean technology, like solar panels and other green equipment, will start flooding into the country. However, if the domestic human capital lacks trained engineers, technicians, or project managers, then no one knows how to set up machinery, operate it optimally, or repair it when needed. Then, this expensive green technology will end up in the storerooms as a total waste. Globalization brought green technology to the adoption stage, but insufficient human capital resulted in little to no adoption.

(2) High Human Capital: If a country opens its border, then the imported advanced clean technology will start flooding into the country again, but if the domestic human capital is highly skilled and has STEM education, then they can easily not install it but repair it locally, and make some modifications in the technology according to the requirements of the country. This creates a multiplier effect, as the country not only uses the technology but also masters it, accelerating the adoption of renewable energy. Consequently, domestic human capital acts as a critical conditioning factor shaping the impact of globalization on sustainable technology uptake. This baseline relationship provides a strong empirical rationale for introducing interaction terms into our dynamic panel data mode

3.4: Theoretical Rationale for Control Variables

A theoretical framework is provided to justify choosing control variables, ensuring the unbiased and accurate isolation of human capital's moderating effect on the relationship between globalization and green technology adoption. Each control variable is selected based on well-established economic theories. :

(1) GDP per Capita: This measure captures the macroeconomic development level within emerging nations. Grounded in the EKC framework, its inclusion assumes that rising income levels afford countries the financial flexibility to invest heavily in clean technologies. We therefore hypothesize a positive correlation between GDP per capita and the integration of green technology.

(2) CO2 per Capita: This acts as a proxy of the pollution due to the existing energy infrastructure. Therefore, high carbon emissions signal a carbon lock-in scenario. Economies highly dependent on fossil fuels for energy production find it difficult to shift because of huge sunk costs and political/institutional constraints. Thus, a negative relationship is anticipated.

(3) Urbanization: This describes the migration of people from rural regions to urban areas seeking a better quality of life. However, this shift worsens energy consumption patterns. Evidence shows that urbanization in developing countries raises electricity demand. This leads these countries to rely more on non-renewable sources, such as fossil fuels, to meet that demand. As a result, urbanization can hinder the growth of green energy infrastructure and harm clean energy adoption

(4) Institutional Quality: This factor considers the effectiveness, reliability, and equity of a country's laws, governance, and regulations. Better Institutional Quality means less corruption and the effective use of funds for sustainable projects, rather than their waste. Therefore, we can expect a positive relationship.

4. Data, Variables, and Estimation Framework

This section maps out the conceptual specification and data channels employed in the empirical analysis. Furthermore, it defends the selection of the specific econometric techniques utilized to address the core research questions.

4.1 Data Description

The empirical foundation of this study rests on an annual panel dataset spanning 25 emerging market economies from 2000 to 2021, aligning with the International Monetary Fund's (IMF) World Economic Outlook classifications. This specific country-year matrix was determined strictly by data accessibility across several prominent repositories. Investigating these developing nations is highly relevant because their accelerating industrial footprint and deepening global ties occur against a backdrop of intensifying ecological stress and disparate human capital reserves.

To operationalize the dependent variable—Green Technology Adoption—this analysis utilizes the ratio of renewable energy consumption to total energy utilization, sourced from the World Bank’s World Development Indicators (WDI). This metric effectively captures a state's structural transition toward sustainable energy alternatives. The primary explanatory variables comprise four dimensions of globalization: economic, trade, financial, and social integration. Each is evaluated through distinct model specifications using the *de facto* measures from the KOF Globalization Index. To account for local workforce capabilities, the analysis incorporates the Human Capital Index from the Penn World Table database. Finally, to ensure robust empirical estimates, the model incorporates a suite of control variables from the WDI, including urbanization, per capita GDP, and per capita carbon dioxide (CO2) emissions, as well as the Liberal Democracy Index from the V-Dem Dataset to capture institutional quality. The precise definitions and configurations of these indicators are organized in Table 1

Table 1 Variables and their description

Variable Label	Operational Definition & Metric	Source Repository
Green Technology Adoption	Renewable energy Consumption as a percentage of total final energy consumption	World Development Indicators(WDI), World Bank
Human Capital	Human Capital Index	Penn World Table (PWT)
Economic Globalization	*De facto* Economic Globalization Index	KOF Swiss Economic Institute
Trade Globalization	*De facto* Trade Globalization Index	KOF Swiss Economic Institute
Financial Globalization	*De facto* Financial Globalization Index	KOF Swiss Economic Institute
Social Globalization	*De facto* Social Globalization Index	KOF Swiss Economic Institute
Urbanization	Urban population as a share of the total Population	World Development Indicators(WDI), World Bank
GDP per capita	Gross Domestic Product per capita adjusted to constant 2015 USD	World Development Indicators (WDI), World Bank
Institutional Quality	Liberal Democracy Index	V-Dem Institute Dataset
CO2 per capita	Per capita carbon dioxide emissions, omitting LULUCF factors (measured in metric tons of CO2 equivalent)	World Development Indicators (WDI), World Bank

4.2 Model

This study aims to evaluate the individual impacts of four globalization types—economic, trade, social, and financial—on the adoption of green technology.

Furthermore, we seek to understand how the interaction of each of these forms of globalization with a country's human capital index influences green technology adoption in emerging economies (which shows the moderating impact of human capital in the globalization-green technology adoption nexus). As green technology adoption is a dynamic process, it tends to be persistent, meaning last period's adoption often influences this period's decision regarding clean energy adoption. Ignoring this phenomenon would lead to misleading interpretations and results. Thus, we specify a dynamic panel model for each dimension of globalization as:

$$\log(GTA_{it}) = \alpha + \beta_1 \log(GTA_{i,t-1}) + \beta_2 GLOB_{it} + \beta_3 (GLOB_{it} \times HC_{it}) + \gamma X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

Where,
$\log(GTA_{it})$ = natural logarithm of green technology adoption for the country i in year t (dependent variable)
$\log(GTA_{i,t-1})$ = one-period lag of the dependent variable (captures persistence)
$GLOB_{it}$ = each form of globalization (economic, trade, social, or financial), estimated in separate models
$GLOB_{it} \times HC_{it}$ = interaction term between globalization and human capital, whose β_3 captures the moderating role of human capital
X_{it} = vector of control variables comprising urbanization, GDP per capita, CO_2 per capita, and institutional quality
μ_i = country-specific fixed effects
τ_t = time-specific fixed effects
ε_{it} = idiosyncratic error term
Using the equation specified above, four separate models, one for each form of globalization, are estimated. To address nonessential multicollinearity arising from interactions between globalization dimensions and the human capital variable, we mean-centered the individual variables before forming the interaction term, following the methodology of Aiken and West (1991) and Brambor et al. (2006). By applying this approach, we mitigate potential multicollinearity issues between the interaction terms and their individual components, all while preserving the fundamental meaning and direction of the model's moderating mechanics

4.3 Dynamic Panel estimation and use of System GMM

Estimating the above model with traditional panel techniques will be inappropriate. This section explains why System GMM is best suited to our study and presents the mathematical formulation of the System GMM model, including its moment conditions for the differenced and level equations.

4.3.1 Why System GMM is used: Justification

The main difficulty in our model lies in managing a lagged dependent variable that captures ongoing green technology adoption over time. Incorporating this lagged variable creates correlation with unobserved, country-specific fixed effects, which breaches the strict exogeneity assumption necessary for the consistent application of standard panel estimators.

Estimating a dynamic panel model with a lagged dependent variable poses significant econometric challenges, rendering standard estimators inappropriate. Employing standard Pooled OLS without accounting for unobserved country-specific heterogeneity leads to an upward bias in the coefficient of the lagged dependent variable, driven by the omitted variables. Conversely, applying a Fixed Effects (FE) within-transformation eliminates these time-invariant country characteristics but introduces an endogeneity problem. Specifically, the transformed lagged dependent variable becomes negatively correlated with the idiosyncratic error term. This induces the well-known Nickell (1981) bias, a downward distortion that remains problematic unless the time dimension (T) approaches infinity.

To circumvent these issues, the first-difference GMM estimator developed by Arellano and Bond (1991) removes the fixed effects via differencing. However, macroeconomic indicators—such as institutional quality or human capital indices—are highly persistent and evolve slowly over time. In the presence of such near-unit-root behavior, lagged levels serve as weak instruments for the subsequent first differences. This weak-instrument problem manifests as severe finite-sample bias and a substantial loss in estimation efficiency.

To simultaneously resolve these estimator biases and weak-instrument limitations, this study utilizes the two-step System GMM framework established by Arellano and Bover (1995) and Blundell and Bond (1998). This approach estimates a simultaneous system of equations in both first differences (instrumented with lagged levels) and levels (instrumented with lagged differences), thereby dramatically improving instrument strength.

We favor the two-step System GMM over its one-step counterpart. While the one-step estimator assumes a homoscedastic weighting matrix, the two-step variant leverages first-stage residuals to construct a weighting matrix that is robust to arbitrary heteroscedasticity, thereby optimizing asymptotic efficiency. Finally, because traditional two-step GMM standard errors can exhibit a severe downward bias in small cross-sectional samples (here, $N = 25$), we systematically apply the Windmeijer (2005) finite-sample correction. All reported standard errors are clustered at the country level, ensuring robustness to both heteroscedasticity and serial correlation within panels.

4.3.2 Methodology

The System GMM framework simultaneously utilizes equations specified in both first differences and levels. The baseline dynamic panel model in levels is expressed as:

$$y_{it} = \gamma y_{i,t-1} + \beta_1 X_{it} + \beta_2 Z_{it} + \eta_i + \varepsilon_{it}$$

Where i denotes the cross $-$ sectional unit (country); t represents the time period. The dependent variable y_{it} represents Green Technology Adoption, and $y_{i,t-1}$ It's a one-year lag. The vector X_{it} captures a set of endogenous or predetermined explanatory variables, while Z_{it} represents a vector of strictly exogenous control variables. The error structure is composed of η_i, which accounts for unobserved

country-specific fixed effects, and ε_{it}, which represents the idiosyncratic white-noise error term.
To eliminate the time-invariant fixed effects (μ_i), we apply a first-difference transformation to the baseline model:

$$\Delta y_{it} = \gamma \Delta y_{i,t-1} + \beta_1 \Delta X_{it} + \beta_2 \Delta Z_{it} + \Delta \varepsilon_{it}$$

While $\text{first} - \text{differencing successfully removes}\ \eta_i$, but it introduces a correlation between the transformed lagged dependent variable $\Delta y_{i,t-1} = \left(y_{i,t-1} - y_{i,t-2}\right)$and the transformed error term $\Delta \varepsilon_{it} = \left(\varepsilon_{it} - \varepsilon_{i,t-1}\right)$through the $y_{i,t-1}$ component. Assuming that the idiosyncratic error ε_{it} exhibits no serial uncorrelated, lagged levels of the dependent and endogenous variables from the period $t-2$ become deeper, serve as valid instruments for our analysis.
The resulting population moment conditions for the first-differenced equation are defined as :

$$E\left(y_{i,t-s} \Delta \varepsilon_{it}\right) = 0 \quad \text{for } t \geq 3 \text{ and } s \geq 2$$

Similarly, if a regressor in X_{it} is endogenous, its lagged levels are instrumented following the same timing structure:

$$E\left(X_{i,t-s} \Delta \varepsilon_{it}\right) = 0 \quad \text{for } t \geq 3 \text{ and } s \geq 2$$

When the independent variables are highly persistent over time, their lagged levels act as weak predictors of the subsequent first differences, leading to considerable finite-sample bias in the standard Difference GMM estimator. System GMM resolves this issue by merging the original level equation with the differenced equation into a unified system.

For the equation in levels, the unobserved individual effect η_i remains in the composite error term $u_{it} = \eta_i + \varepsilon_{it}$. Therefore, the instruments chosen for this equation must be orthogonal to η_i.Blundell and Bond (1998) introduce a crucial initial condition assumption: though the variables' levels may be related to η_i The initial differences of these variables are uncorrelated with the fixed effects, indicating that the data-generating process is in a steady state.
Formally, the initial condition is expressed as:

$$E(\Delta y_{i2} \eta_i) = 0 \quad \text{for all } i = 1, \dots, N$$

This assumption provides additional, non-redundant moment conditions for the level equation, thereby making lagged first differences valid instruments for it.

$$E\left(\Delta y_{i,t-1} (\eta_i + \varepsilon_{it})\right) = 0 \quad \text{for } t \geq 3$$

For any endogenous regressors in X_{it} , The corresponding moment conditions for the level equation are similarly specified as:

$$E\left(\Delta X_{i,t-1}(\eta_i + \varepsilon_{it})\right) = 0 \quad \text{for } t \geq 3$$

4.5 Diagnostic testing

To ensure the statistical validity and consistency of our two-step System GMM estimations, we perform three essential post-estimation diagnostic tests across all four specifications:

- **Arellano-Bond Test for Serial Correlation:** This test evaluates the presence of first-order [AR(1)] and second-order [AR(2)] serial correlation within the first-differenced residuals. Due to the mathematical structure of the differenced error term, we expect the AR(1) to be statistically significant. Conversely, a failure to reject the null hypothesis for the AR(2) model (indicated by a high p-value) confirms the absence of second-order serial correlation and validates the instrument lag structure (Arellano & Bond, 1991).
- **Hansen Test of Overidentifying Restrictions:** This test evaluates the joint validity of the instrument set and the underlying exclusion restrictions. A non-significant p-value indicates that the instruments are properly exogenous and uncorrelated with the error term, confirming proper model specification (Sargan, 1958; Hansen, 1982).
- **Instrument Count Verification:** An excessive number of instruments can severely weaken the diagnostic power of the System GMM estimator, particularly when the instrument count expands alongside the time dimension (T) and surpasses the cross-sectional sample size (N). Instrument proliferation risks overfitting the endogenous regressors and can artificially inflate the Hansen test p-value toward 1.00, masking instrument invalidity (Roodman, 2009a, 2009b). We actively monitor and restrict the instrument count to preserve test reliability.

5. Results & Discussion

This section presents the empirical findings obtained from the two-step System GMM estimations

5.1 System GMM results for models

Table 2-5 shows the System GMM results for economic, social, trade, and financial globalization.

Table 2 presents the results of Model 1, the economic globalization model, which explores how human capital influences the relationship between economic globalization and green technology adoption in emerging economies. Notably, the one-period lag of $\log(GTA_{it})$has a positive and significant effect on its current-year value at the 1% significance level. This shows that a 1%change in the previous year's period value leads to a change in the current value of $\log(GTA_{it})$by 0.695% increase, all else being equal. Evidence indicates that economic globalization alone has no significant effect on green technology adoption (β = 0.002, p > 0.10). This suggests that factors such as trade openness and financial liberalization alone may not be sufficient to foster green technology adoption; the interaction between economic globalization and human capital has a positive and highly significant impact. (beta = 0.009, $p < 0.05$), supporting H1 and suggesting that economic globalization promotes green technology adoption when there is sufficient highly skilled human capital. These findings support the absorption capacity hypothesis, that a skilled and educated work force is needed to effectively utilize the knowledge spillover generated through global economic integration (Cohen & Levinthal, 1990)

Table 2. Results of Model 1: Baseline system GMM estimates (Economic Globalization)

Variables	$\log(GTA_{it})$
$\log(GTA_{i,t-1})$	0.695*** (0.111)
Economic_Glob	0.002 (0.002)
Economic_Glob_x_Human_capital	0.009** (0.004)
GDP_per_capita	0.000*** (0.000)
Urbanization	-0.006** (0.002)
CO2_per_Capita	-0.132*** (0.038)
Institutional_quality	0.460* (0.246)
Constant	1.284*** (0.435)

*Significance levels are denoted as follows: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.*

GDP per capita (β = 0.000, $p < 0.01$) and institutional quality (β = 0.460, $p < 0.10$) both have positive and significant effects on green technology adoption. Conversely, urbanization (β = −0.006, $p < 0.05$) and CO_2 emissions per capita (β = −0.132, $p < 0.01$) have notable negative effects. These findings support expectations: higher GDP per capita tends to correlate with increased green tech adoption, consistent with the Environmental Kuznets Curve Hypothesis, which suggests wealthier nations invest more in clean energy technologies (Grossman & Krueger, 1995). Stronger institutional quality also correlates positively, as effective governance and stability promote the enforcement of environmental regulations vital for adopting clean technologies (Ofoeda et al., 2024). On the other hand, rising per capita CO2 emissions hinder green tech adoption due to carbon lock-in, where economies dependent on fossil fuels encounters high costs and difficulties in transitioning to green energy. Additionally, urbanization negatively impacts adoption, as expanding urban populations drive up energy demand and infrastructure needs, often diverting resources from green investments.

Table 3 Results for Model 2: Baseline system GMM estimates (Social Globalization)

Variables	$\log(GTA_{it})$
$\log(GTA_{i,t-1})$	0.746*** (0.097)
Social_Glob	0.002 (0.003)
Social_Glob_x_Human_capital	0.006** (0.003)
GDP_per_capita	0.000*** (0.000)
Urbanization	-0.004* (0.002)
CO2_per_Capita	-0.082** (0.034)
Institutional_quality	0.328 (0.253)
Constant	0.993** (0.386)

*Significance levels are indicated by * for p < 0.10, ** for p < 0.05, and *** for p < 0.01.*

Table 3 displays the outcomes of the social globalization model, emphasizing how human capital influences the connection between social globalization and green technology adoption in emerging economies. The one-year lag significantly affects its current value at the 1% significance level. Specifically, a 1% rise in the previous year's value results in a 0.746% increase in the current value, ceteris paribus. The evidence indicates that social globalization has a positive but not significant relationship with green technology adoption ($\beta = 0.002$, $p > 0.10$). This suggests that simply sharing information, cultures, people, and ideas across borders is insufficient to promote the adoption of green technology in these economies. Nonetheless, the model's moderating influence is both positive and highly significant ($p < 0.05$). This confirms H2 and indicates that social globalization promotes green technology adoption when skilled human capital is present. Regarding the control variables, their signs and significance levels are consistent with the economic globalization model, except for institutional quality, which stays insignificant.

Table 4 Model 3 Results: Baseline System GMM Estimates (Trade Globalization)

Variables	$\log(GTA_{it})$
$\log(GTA_{i,t-1})$	0.858*** (0.093)
Trade_Glob	0.000 (0.001)
Trade_Glob_x_Human_capital	0.006** (0.003)
GDP_per_capita	0.000** (0.000)
Urbanization	-0.00 (0.003)
CO2_per_Capita	-0.065* (0.034)
Institutional_quality	0.236 (0.237)
Constant	0.545 (0.387)

*Significance levels are indicated as * for p < 0.10, ** for p < 0.05, and *** for p < 0.01.*

The trade globalization model, presented in Table 4, investigates how trade globalization influences the adoption of green technology in emerging economies. Notably, it considers the impact of the log of trade globalization with a one-period lag of $\log(GTA_{it})$has a positive and there is a significant effect on its current value at the 1% level, meaning that a 1% increase in the previous year's value results in approximately a 0.858% rise in the current period, all else being equal. The data show that trade globalization has a positive but statistically insignificant relationship with green technology adoption. (β = 0.000, $p > 0.10$), indicating that cross-border movement alone is insufficient to promote adoption in emerging economies. In contrast, the interaction between trade globalization and human capital is both positive and statistically significant (β = 0.006, $p < 0.05$) in its influence on green technology adoption, thereby supporting H3. This indicates that trade globalization encourages the adoption of green technology, particularly when a country has a high level of skilled human capital. Among the control variables, their signs and significance are consistent with the economic globalization model, except that institutional quality and urbanization are insignificant in this context.

Table 5 Results for Model 4: Baseline system GMM estimates (Financial Globalization)

Variables	$\log(GTA_{it})$
$\log(GTA_{i,t-1})$	0.673*** (0.080)
Financial _Glob	0.005*** (0.002)
Financial _Glob_x_Human_capital	0.010*** (0.003)
GDP_per_capita	0.000** (0.000)
Urbanization	-0.007*** (0.002)
CO2_per_Capita	-0.120*** (0.025)
Institutional_quality	0.531*** (0.135)
Constant	1.376*** (0.336)

*Significance levels are shown as * for p < 0.10, ** for p < 0.05, and *** for p < 0.01.*

After establishing the three globalization outcomes, the focus shifts to the financial aspect of globalization. The System GMM estimates, shown in Table 5, examine how human capital influences the relationship between financial globalization and green technology adoption in emerging economies. Notably, the lag of the log of (GTA_{it}) from the previous year shows a positive, statistically significant effect on its current value at the 1% level. This means that a 1% increase in the previous year's value leads to about a 0.673% increase in the current value of the log, assuming all other factors are unchanged.

Unlike the three models previously discussed, where globalization alone has little effect on green technology adoption, financial globalization shows a clear and significant positive impact ($\beta = 0.005$, $p < 0.01$). This suggests that foreign direct investment and international capital flows independently promote green technology adoption. Additionally, there's a positive and highly significant interaction ($p < 0.01$) between financial globalization and human capital, indicating that the effect of financial globalization is stronger when human capital is highly skilled, supporting H4. The control variables' signs and significance levels are consistent with those found in the economic globalization model.

5.2 Diagnostic tests

Table 6 details the vital diagnostic statistics across all four empirical specifications to verify the consistency and internal validity of the System GMM estimations. The structural integrity of our identification strategy is evaluated against three fundamental criteria: instrument proliferation thresholds, the Hansen test for overidentifying restrictions, and the Arellano-Bond tests for residual autocorrelation.

- A primary risk in System GMM estimation is instrument proliferation, which can weaken the power of overidentification tests and cause severe overfitting of endogenous regressors. As established by Roodman (2009a), the instrument count must be strictly less than the number of cross-sectional units (N). Across all four specifications, the generated instrument sets remain comfortably below our sample size of 25 countries. This conservative instrument footprint prevents the artificial inflation of diagnostic test statistics and ensures that the finite-sample standard errors remain uncompromised.
- The Hansen J-test is utilized to evaluate the joint validity of our internal instruments and their corresponding exclusion restrictions. Across all four models, the test fails to reject the null hypothesis of joint instrument exogeneity, yielding p-values comfortably exceeding the standard 0.10 threshold. This statistical non-rejection demonstrates that the lagged levels and differences chosen as instruments are orthogonal to the idiosyncratic error term. This outcome confirms the correct specification of the moment conditions; rejecting this null hypothesis would have invalidated our central identification strategy.
- First-Order Autocorrelation [AR(1)]: As expected, the Arellano-Bond test rejects the null hypothesis of no first-order serial correlation across all four models. This significant AR(1) result is a mathematical artifact of the first-differencing transformation, which mechanically introduces correlation between adjacent differenced errors and does not indicate model misspecification.
- Second-Order Autocorrelation [AR(2)]: Critically, all four specifications pass the AR(2) test, producing p-values well above the 0.05 significance level. The absence of second-order autocorrelation in the differenced residuals confirms that the underlying errors in levels behave as white noise. This is the crucial requirement that justifies the use of twice-lagged variables (t-2) as valid internal instruments.

Table 6: Results from the Diagnostic Tests

Tests	Economic Globalization Model	Social Globalization Model	Trade Globalization Model	Financial Globalization Model
AR(1)	0.010**	0.005***	0.003***	0.010**
AR(2)	0.396	0.138	0.193	0.514
Hansen Test	0.553	0.597	0.237	0.976
Number of Instruments	14	24	24	14

*Significance levels: * for p < 0.10, ** for p < 0.05, *** for p < 0.01.*

6: Conclusion and implications

This study demonstrates that globalization alone is an insufficient vehicle for ecological modernization in developing nations. By evaluating the interactions between multiple dimensions of global integration—specifically trade, financial, social, and economic facets—and the adoption of green technologies, the empirical evidence reveals that domestic human capital serves as the vital link. Utilizing a robust two-step system GMM panel-data methodology to control for endogeneity and unobserved heterogeneity, the analysis confirms that international technology transfers fail to yield significant environmental returns without a highly capable local workforce. Ultimately, cross-border green innovations can only be successfully absorbed, maintained, and optimized when paired with targeted domestic expertise. Without this localized capacity, the external costs of technology adoption remain prohibitively high, making sustainable development an elusive goal for emerging economies.

Based on these results, the study recommends the following policies: First, the government should not focus solely on trade liberalization, increasing FDI, the movement of cross-border ideas, and importing high-tech technology; it should collaborate with the education ministries to ensure that whenever a green technology policy is implemented, the domestic workforce is trained simultaneously to reduce skill-mismatch situations. Second, when a country adopts green technology from foreign multinational firms, it should not only purchase the technology but also enter into contracts to train local workers for its construction, maintenance, and operation. Third, the government can offer tax incentives to companies that invest in upgrading their employees' skills in green technology. Finally, greater emphasis should be placed on STEM education and green job certification, with a focus on practical skills such as installing solar panels and manufacturing green technologies. Developing a highly skilled local workforce reduces reliance on foreign experts for high-tech projects and helps lower overall project costs.

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