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The heterogeneous impacts of environmental technologies and research and development spending on green growth in emerging economies: the moderating role of financial globalization

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Introduction: Understanding the heterogeneous impacts of environmental technologies (ETs), research and development (RD) spending and financial globalization (FG) on green economic growth (GEG) is worthwhile to promote progress toward GEG. Besides, exploring the moderating role of FG is essential to uncover the nuanced dynamics that shape the relationship between ET, RD, GEG, and the influence of global financial integration. Thus, this study examines the effects of ET, RD and FD on GEG in emerging market economies (EMEs). In addition, we investigate the moderating role of FG on the effects of ETs and RD on GEG.

Methods: The method of moments quantile regression (MMQR) is applied using a fixed effects model that can capture distributional heterogeneity and nonnormality concerns for the panel of 25 EMEs from 2000 to 2019. In addition, other alternative models are applied to conduct robustness analysis. We use green total factor productivity (GP) to proxy for GEG using the Malmquist–Luenberger Productivity Index (MLPI) strategy based on the directional distance function (DDF).

Results and discussion: The findings imply that ETs significantly impact GEG, revealing evidence that promoting environmental innovation positively contributes to GEG progress in EMEs. Likewise, RD promotes GEG progression in EMEs. Additionally, FG positively impacts GEG. FG also positively moderates the effects of ETs and RD on GEG, implying that countries open to FG can better harness the positive roles of investment in

Abbreviations: CO_2, Carbon dioxide; DDF, Directional Distance Function; DMU, Decision-Making Unit; EME, Emerging Market Economies; ET, Environmental Technologies; EU, European Union; FDI, Foreign Direct Investment; FD, Financial Globalization; FMOLS, Fully Modified Least Square; GDP, Gross Domestic Product; GMM, Generalized Method of Moments; GP, Green Total Factor Productivity; IMF, International Monetary Fund; ECH, Malmquist-Luenberger Efficiency Change; TCH, Malmquist-Luenberger Technical Change; MLPI, Malmquist-Luenberger Productivity Index; OECD, Organization for Economic Cooperation and Development; MMQR, Method of Moments Quantile Regression; RD, Research and Development; SDG, Sustainable Development Goals; UNESCO, United Nations Educational, Scientific and Cultural Organization; WDI, World Development Indicator.

ETs and RD on GEG in EMEs. Therefore, policymakers should develop prudent policies to encourage ETs and RD to promote GEG in EMEs, which aligns with the goals of controlling climate variation (SDG-13) and fostering innovation (SDG-9) to promote GEG in EMEs.

KEYWORDS

green economic growth (GEG), environmental technologies (ETs), research and development (RD), financial globalization (FG), emerging market economies (EMEs) acronyms CO_2 carbon dioxide

1 Introduction

The promotion of GEG has significant theoretical and practical implications for countries. Green growth is aimed at decoupling economic growth from environmental impacts (Fletcher and Rammelt, 2017), as it relies on the assumption that economic performance and environmental development can concurrently improve (Bina, 2013). Therefore, the development of low-carbon, resource-efficient, and socially inclusive green economies is encouraged to promote GEG, and GEG serves as a crucial roadmap for sustainable development in nations worldwide (Liang and Qamruzzaman, 2022).

In light of the current ecological issues, EMEs have increased their resource and energy efficiency to limit pollution-producing outputs and promote GEG. These countries have grown substantially and are striving for rapid expansion (OECD, 2017). However, exploiting natural resources degrades the environment and is a major growth factor. Thus, economic growth negatively impacts environmental quality during the initial stage of economic development (see Supplementary Figure SA1). For instance, the top ten nations in the Organization for Economic Cooperation and Development (OECD) in terms of the contribution of subsoil assets to economic growth and their partner nations are all EME countries (OECD, 2017).

Furthermore, little progress has been made regarding resource use efficiency and productivity (Capozza and Samson, 2019). Additionally, resource-based economic activity frequently results in environmental conflicts for EMEs. Regarding global environmental conflicts, some EME members are among the top fifteen nations (Capozza and Samson, 2019). However, some of these countries have implemented new GEG initiatives and policies to improve their environmental performance and economic growth, and rising environmental destruction and resource depletion pose serious threats.

Theoretically, it is argued that ETs play a decisive role in fostering growth (Solow, 1956). ETs represent the number of patents connected to environmental-related technology development and are important indicators of a nation's innovative capacity (Fernandes et al., 2021; Hussain et al., 2022). The theoretical relationship between ETs and GEG can be elucidated through the lens of endogenous growth theory, which predicts increasing returns to scale in innovation, thereby fostering long-term knowledge-based growth (Cortright, 2001) and ecological modernization theory frameworks, which argues that promoting environmental-related innovation promotes GEG (Jänicke, 2020). This theory is consistent with a Green Solow model by Brock and Taylor (2010) that could be adapted to endogenize the abatement function. Moreover, according to growth theories, a sustainable growth path can be established by fostering technical innovation through patents, innovations, and taxes (Acemoglu et al., 2016).

By creating new strategies for sustainable development and pollution control that significantly reduce the environmental cost of economic growth, ETs promote GEG (Hart, 1995). Additionally, growth theories suppose that a sustainable growth path can be established by promoting technical innovation (Acemoglu et al., 2016).

Empirically, some scholars argue that ET investments are vital mechanisms and important means of achieving GEG (Fang et al., 2022; Fletcher and Rammelt, 2017; Fernandes et al., 2021). In other words, ET investment contributes to GEG by promoting cutting-edge innovations in technology and business that have a positive effect on society and the planet (Adams et al., 2016; Zhao et al., 2022) and mitigating the adverse effects of energy consumption (Jin et al., 2019; Wang and Wang, 2019). Additionally, Fernandes et al. (2021), Sohag et al. (2021), and Nosreen et al. (2021) inferred that ETs play a role in GEG in both OECD and EU countries. In contrast, other scholars argue that ETs negatively affect GEG progress by increasing carbon emissions (Santra, 2017). It is also argued that ETs contribute to the depletion of ecological resources, resulting in the deterioration of GEG progress. These adverse impacts on GEG are due to technological or energy rebound effects (Van der Ploeg, 2011). Additionally, Wang and Wei (2020) provided evidence that the promotion of ETs can negatively affect environmental quality and GEG progress through the energy rebound effect. Therefore, despite the empirical studies reviewed in this paper, economists still have no clear consensus regarding the impacts of ETs on GEG in EMEs, and the results remain inconclusive.

Moreover, because of its effect on innovation in many areas of the economy, RD has piqued the attention of scholars and researchers (Han et al., 2023). RD denotes current and capital investments in experimental, fundamental, and applied research. Spending on RD reflects the allocation of public financial resources toward research concerning the environmental dimensions of the economy (UN, 2006; Alvarado et al., 2021).

Theoretically, the connection between RD and GEG is based on the notion that increased RD spending leads to developments in environmentally friendly innovation, including the promotion of green energy production, which can significantly contribute to GEG (Lee and Min, 2015). Moreover, the connection between RD and GEG is established within endogenous growth theory, which posits that investing in RD and innovation facilitates sustained knowledge-driven growth (Aghion and Howitt, 1997).

Additionally, the promotion of RD enhances GEG progress through the foundation of creative ideas and knowledge and contributes to ecological sustainability (Alvarado et al., 2021; Kihombo et al., 2021; Jiang et al., 2023). Therefore, RD investment can provide green means and low-emissions strategies, ultimately affecting GEG (Jiang et al., 2023). Additionally, RD investments can facilitate this increase by promoting the development of the latest technologies for limiting CO_2 emissions (Ma et al., 2022). Moreover, RD is an essential component of innovation that further develops human resources and knowledge assets and increases innovation capacity (Irfan et al., 2021; Boeing et al., 2022). Although these studies have been conducted to investigate the impacts of RD on GEG, they have primarily been focused on advanced countries and only a few emerging markets.

Furthermore, the impacts of globalization on GEG progress have led to unresolved empirical puzzles, some of which have exerted positive effects on the environment and economic activity (Solarin et al., 2017; Haseeb et al., 2018; Shahbaz et al., 2018) and adverse effects on environmental quality (Urom et al., 2022). On the one hand, promoting the flow of commodities and services, investment, economic activities, and urbanization due to globalization negatively affects GEG, as these activities require greater consumption of energy and other resources (Solarin et al., 2017; Haseeb et al., 2018; Shahbaz et al., 2018). Trade globalization boosts investments in clean energy and reduces CO_2 emissions, which can help drive GEG (Ahmed et al., 2022).

On the other hand, FG, which brings foreign capital accompanied by skills and creativity that can facilitate the transition to cleaner and safer energy sources and improved environmental quality, promotes GEG (Urom et al., 2022). The broad effect of financial development is demonstrated through FG (Gygli et al., 2019). Additionally, in the current age of globalization, ETs being used in particular countries can be adopted by other countries as a result of spillover effects (Pineiro-Chousa et al., 2019). Therefore, by increasing the financial flow to green innovation, FG can moderate the ET-GEG nexus (Chen et al., 2023a). In addition, FG stimulates the links between financial flow and RD-led clean production activities, thus promoting GEG (Sbia et al., 2017). FG increases the incentives for scientific RD associated with FDI (Dauvergne and Lister, 2012), which promotes the flow of financial capital that can be used to solve the financial constraints of RD and drive investment in ETs (Deng and Zhao, 2022). Specifically, FG and ETs support each other (Majeed et al., 2022). In other words, an efficient and thriving financial sector provides convenient access to a diverse array of financial services and products that can support RD operations, improve ETs, and further develop renewable energy initiatives with the potential to significantly enhance GEG (Murshed, 2020). However, Wang et al. (2021) found a negative impact of FG on industrial sector green productivity due to spillover effects. Previous studies have attempted to separately link globalization to environmental quality and economic growth; however, research on the impacts of FG on GEG in EMEs and the moderating role of FG in the relationships among RD, ETs and GEG is limited. Therefore, investigating how ETs, RD and FG influence GEG specifically within EMEs is worthwhile. The extent of the analysis of the effects of ETs, RD and FG on GEG in EMEs remains limited in the literature. Moreover, assessing the effects of ETs, RD and FG on GEG gains substantial significance within the context of the SD framework. Promoting ETs, RD, and FG aligns with SD objectives, particularly SDG-13, SDG-9 and SDG-8, emphasizing the imperative of reducing emissions, fostering innovation, and promoting sustainable economic growth (UN, 2006). Also, despite all the empirical studies, there is no clear consensus among economists on the impacts of ETs, RD and FG on GEG and remains rather inconclusive. This is because different studies use different methods and timeframes and focus on different countries, mostly advanced economies with a few developing ones. Thus, this study is motivated to fill this gap by examining the impacts of ETs, RD and FG on GEG in emerging economies. We chose EMEs based on the following facts. First, EMEs had the fastest economic growth in the last 30 years, contributing around 60% to global GDP growth, and they are also newly industrialized (Lin and Wang, 2019; Borojo et al., 2023). Second, the rapid growth has led to challenges like increased energy use, depletion of natural resources, and low progress in resource efficiency and productivity. Besides, environmental conflicts related to resource-based economic activities have also challenged progress in GEG in these economies (Capozza and Samson, 2019; Khattak et al., 2020; Borojo et al., 2023). Third, EMEs are significant contributors to CO_2 emissions, accounting for about half of emissions over the last 3 decades. Their ecological footprint, or environmental impact, has grown faster than the world average. Lastly, despite these challenges, EMEs have significantly increased the growth rate of new technologies compared to other parts of the world (Borojo et al., 2023).

Thus, against this background, this study deals with solving the following specific questions. First, what are the effects of ETs on GEG progress in EMEs? Second, does RD contribute to the progress toward GEG in EMEs? Third, how does FG moderate the impacts of ETs and RD on GEG in EMEs? Motivated by these research questions, this study aims to provide fresh evidence regarding the effects of ETs, RD, and FG on the GEG progress of 25 EMEs using data from the 2000 to 2019 period. We regress ETs, RD, FG and other control variables with GEG progress using the MMQR with fixed effects as proposed by Machado and Silva (2019). We use the MMQR to control for individual heterogeneity and distributional heterogeneity. We further investigate the moderating role of FG on the impacts of ETs and RD on GEG. These findings imply that the GEG of EMEs is positively affected by ETs, RD and FG. Additionally, countries are more open to FG because of the positive impacts of ETs and RD on GEG. The analysis is repeated using the two-step GMM system, the FMOLS and Tobit models to control for endogeneity concerns and to obtain long-term estimates. Our findings indicate that ETs, RD and FG have a robust positive impact on GEG, showing evidence that ETs, RD and FG promote GEG advancement in all quantiles in EMEs. Furthermore, our analysis of the moderating role of FG on the effects of ETs and RD on GEG highlights that the FG positively moderates the relationship. Therefore, the practical implications of this study lie in navigating these findings, emphasizing the importance of well-designed and evaluated policy actions to integrate ETs and RD in the FG framework to harness GEG in EMEs.

This study contributes to the current literature in several ways. First, to the best of our awareness, this is the first study to examine the impacts of ETs, RD and FG on the GEG of several EMEs. Hence, this paper is valuable since it offers a greater understanding of the effects of ETs, RD and FG on GEG in EMEs, which account for more CO_2 emissions than advanced economies and are more likely to suffer from environmental disasters (Ullah et al., 2022). Therefore, by focusing on EMEs, the study can provide valuable insights into how these factors interact and influence green growth in contexts that have been less explored.

The second greatest contribution is the study's investigation of the moderating effect of FG on the effects of ETs and RD on GEG, which is a noteworthy undertaking. As we revisit this relationship in light of the moderating role of FG on the impacts of ETs and RD on GEG, this study advances the theoretical and empirical literature on the impacts of ETs, RD and FG on GEG. Third, we derive a GP indicator using the MLPI method based on the directional distance function (DDF). Fourth, unlike earlier studies, this study uses a more specific FG index proposed by Gygli et al. (2019). The use of FG thus enables us to account for the impact of financial openness on GEG in EMEs, in contrast to the conventional approach of using either of the two composite indices of globalization.

Fifth, applying the MMQR with fixed effects to capture heterogeneity and nonnormality represents an interesting endeavour of this study. This strategy is justifiable due to the GEG heterogeneity of EMEs. Therefore, applying a model that can incorporate individual and distributional heterogeneity across the conditional quantiles of GEG progress is worthwhile because it provides an estimation of the differential effects of globalization and ETs on GEG for countries with various current GEG levels. It also employs a panel data model, namely, the two-step system GMM, the Tobit model under the FMOLS method, for robustness tests.

Therefore, examining the impacts of ETs and RD on GEG in EMEs with a focus on the moderating impact of FG presents innovative perspectives. This research illuminates how different ET approaches and RD investments influence GEG in EMEs, considering the varied economic contexts in emerging markets. Understanding the role of FG in moderating these connections reveals intricate pathways for promoting sustainable development. This exploration of the role of FG in shaping the effectiveness of environmental initiatives offers crucial insights for policymakers and stakeholders, contributing to a holistic comprehension of how global financial integration intersects with GEG strategies, which is imperative for formulating effective sustainability policies.

The remainder of this study is organized as follows. Section two provides the literature review. Section three presents the data and methodology. Section four contains the results and discussion. Section five provides a robustness analysis. Section six reports the results of the causality test. Finally, section seven presents the conclusions and policy implications.

2 Literature review

2.1 Theoretical literature

The concept of the green economy appears to constitute a new ecological conservation and modernization terminology. This concept has been accepted worldwide as a requirement for global sustainable development (Lorek and Spangenberg, 2014). The idea of green economic growth is based on the work of Stavrakakis (1997), who developed the idea of the green economy to address environmental deterioration and provided the framework for a new environmental strategy. As a result, environmental law, policy, and management in the corporate sector all increased during the 1990s.

Then, GEG theory began with the straightforward observation that the natural environment is also a factor of production, but it has been largely disregarded in both classical growth theory and the historical patterns of economic expansion in practice (Solow, 1974). The theory was first proposed as a paradigm, theorizing that achieving GEG necessitates striking a balance between economic activity and the environment. Thus, GEG exemplifies decoupling the effects of economic expansion growth from environmental sustainability (Fletcher and Rammelt, 2017). According to eco-modernization theory, human initiatives can effectively balance economic progress with environmental development (Mol and Sonnenfeld, 2000). Further, this idea was revived after the financial crisis of 2008. Measures taken to improve the environment can help stimulate growth in economies that have been hit hard by the recession (Pollin et al., 2008).

Based on the abovementioned theoretical underpinning, the GEG concept can be understood as a resource-efficient, low-carbon-intensive approach to achieving economic development. Therefore, in the framework of a green economy, economic growth is fueled by public and private green investments that can increase the efficiency of resources and energy, safeguard ecosystems and biodiversity, and stimulate the economy by reducing CO_2 emissions.

The theoretical relationship between innovation and GEG is based on Solow's (1956) model, which depicts the relationship between growth and innovation and implies that innovation plays a decisive role in fostering growth. In addition, Hart (1995) provided a concise definition of the term "ETs," stating that it refers to the process of creating new tools for sustainable development and pollution control that significantly reduce the environmental cost of economic growth, thus promoting GEG. Besides, the association between ETs and GEG is based on endogenous growth theory that forecasts increasing returns to scale in innovation to promote long-term knowledge-based growth (Cortright, 2001). The central tenet of this theory is to explicitly model investment in technological progress and RD (Aghion and Howitt, 1997). Therefore, resource-saving innovations envisioned in most endogenous growth models are likely to be technologies to decrease pollution and conserve the use of raw materials and energy inputs. In this regard, endogenous growth theory supports the sustainability view (Burgess and Barbier, 2001). Besides, Maris and Holmes (2023) added an important dimension to endogenous growth models. By endogenizing technological change, this view of Maris and Holmes (2023) considered how investments in green innovation and RD could shift the growth path. This theory is consistent with a Green Solow model by Brock and Taylor (2010) that could be adapted to endogenize the abatement function.

Moreover, according to growth theories, a sustainable growth path can be established by fostering technical innovation through patents, innovations, and taxes (Acemoglu et al., 2016). However, promoting technological innovation can negatively impact environmental quality and GEG development. Improving energy efficiency, for instance, lowers carbon emissions, but when efficiency gains increase the level of resource and energy use, the rebound effect causes CO_2 emissions to rise as a result of technical advancement (Wang and Wei, 2019).

Furthermore, theoretically, the connection between RD and GEG can be explained by different mechanisms. For instance, increased RD investment leads to advancements in technology in the energy sector and promotes the production of green energy, which can significantly contribute to GEG (Lee and Min, 2015) and energy use efficiency (Ma et al., 2022). In addition, driving GEG through investment in RD can be considered critically important because it plays a vital role in abating CO_2 emissions.

Additionally, FG leads to greater financial openness and economic integration (Agénor, 2004). Through the exchange of commodities and services, information, technology, and foreign direct investment, globalization links nations worldwide (Grossman and Krueger, 1991). By linking nations, globalization encourages economic activity and raises living standards. There are two points of view regarding how globalization affects advancing economies and environmental quality. On the one hand, globalization negatively affects environmental quality by boosting the movement of goods and services, FDI, economic activity, and urbanization, as these activities require greater consumption of energy resources (Solarin et al., 2017; Haseeb et al., 2018; Shahbaz et al., 2018). On the other hand, globalization encourages the diffusion of information and the transition of economies from industry to service, positively impacting environmental quality. The impact of globalization on the environment is discussed in terms of scale, composition, and technology.

Theoretically, FG impacts GEG through three channels such as scale effect, technique effect and composition effect (Ulucak et al., 2020; Chen et al., 2023b). The scale effect delineates how FG amplifies economic endeavours, resulting in heightened consumption of fossil fuels. This, in turn, deteriorates environmental quality, consequently impeding GEG. Conversely, the technique effect channel suggests that by fostering efficient and environmentally friendly green innovations, FG has the potential to mitigate pollution emissions, thereby fostering green growth. The literature also deliberates on another channel, the composition effect, which characterizes a debatable correlation between FG and GEG (Danish et al., 2018; Chen et al., 2023a; Huo et al., 2023). Also, ecological modernization theory aims to safeguard the quality of the environment through resource-efficient innovations (Jänicke, 2020), which can positively influence the progress toward GEG.

Furthermore, FG boosts the allure of RD and tends to improve GEG (Huang et al., 2021). FG is a factor of liberalization, financial openness, and digital financial inclusion. In this sense, the pollution haven and pollution halo hypotheses, which are both significant, explain the connection between globalization and the environment. According to the pollution haven hypothesis, environmentally hazardous enterprises shift their activities from industrialized economies to less-developed countries with lax environmental quality requirements and laws (Doytch and Uctum, 2016). On the other hand, the pollution halo hypothesis claims that FDI and commerce improve the environment by transferring effective management techniques and technologies (Sbia et al., 2014).

2.2 Empirical literature and hypothesis development

2.2.1 Environmental technologies, research and development and green growth

In addition to the theoretical basis discussed in the previous section, several empirical works have been conducted on the impacts of ETs and RD on different aspects of environmental quality and GEG propagation. For example, according to Luo et al. (2022), ETs help to reduce environmental pollution. It has been argued that by positively impacting the economy and environment, ETs meet the requirements of economic actors with fewer negative consequences than traditional alternatives (Adams et al., 2016; Goodman et al., 2017). This perspective encourages ecologically friendly technologies and lowers the cost of environmental sustainability (Popp, 2012). In other words, ETs promote economic development by making sophisticated machinery more accessible and reducing environmental contamination. Thus, ET is a key determinant in promoting GEG (Obobisa et al., 2022). ETs can contribute to GEG by reducing production waste and pollution emissions (Ghisetti and Quatraro, 2017).

Furthermore, Meiling et al. (2020) evaluated how technological innovation affects green total factor productivity (GP) in OECD countries. Their findings suggest that technological innovation significantly boosts GP. Additionally, Onifade and Alola (2022) showed that environmentally related technological innovations have robust CO_2 emission mitigation effects in seven emerging countries. Furthermore, Fernandes et al. (2021) demonstrated how ET encourages GEG by analyzing ETs encourage GEGs by analyzing the contribution made by ETs to GEG using aggregated country-level data from OECD countries. In addition, Ali et al. (2023) examined the effects of ETs on CO_2 in OECD countries and found that they play a significant role in reducing CO_2 in OECD economies.

Similarly, Wei et al. (2023) argued that the environmental quality of most green economies is significantly improved through ET improvement. Chen et al. (2023b) found that ETs significantly help improve the environmental quality of G7 countries. In addition, Ramzan et al. (2023) investigated the effect of ETs on the sustainability of the environment and energy transition in the United Kingdom and found that ETs play a role in improving environmental sustainability.

Similar estimates of the effect of ETs on GEG in European Union nations have been made by Nosreen et al. (2021). Their study indicated that green technology considerably boosts GEG. In addition, Sohag et al. (2021) found that nations with many sustainable inventions are more likely to advance GEG progress. This finding is comparable with the findings of Alola and Onifade (2022), providing evidence that ETs help mitigate carbon emissions in Finland. Zhang et al. (2022) examined the effects of different shocks in innovation on sustainability. Their results reveal that positive technological innovation shocks promote environmental quality, while negative technological shocks adversely affect environmental sustainability. These findings are analogous to the results of Alola and Adebayo (2022), who provided tangible evidence that environment-related technologies mitigate greenhouse gas emissions in Nordic countries.

However, ETs are sometimes thought to constrain the promotion of GEG. This is because these innovative technologies can inadvertently lead to increased energy use and pollution, thus countering the efforts made toward environmental sustainability and reducing green growth (Zhang et al., 2018). Furthermore, some companies prioritize profit over environmental considerations when adopting green innovations to save money on resources such as capital and labor. This pursuit of profit without attention to environmental impacts can escalate pollution and waste and negatively impact green growth (Zhang and Vigne, 2021).

Limited studies have been conducted regarding the impacts of RD, and we could not find any study focusing on this nexus in EMEs using appropriate GEG proxies. However, a few studies have been conducted to investigate its impacts on different aspects of environmental sustainability. For example, Alvarado et al. (2021) suggested that RD exerts a heterogeneous influence on environmental degradation, positively impacting some countries and negatively impacting others. Furthermore, they assert that the innovation mechanisms connected to RD expenditures can produce biodegradable products that only minimally contaminate the soil or emit fewer greenhouse gases. In contrast, Kihombo et al. (2021) revealed that RD is negatively connected to the deterioration of the environment and that expenditures on RD substantially reduce carbon emissions. Additionally, Petrovi and Lobanov (2020a) revealed that an increase in RD investments reduces CO_2 emissions over time. Similarly, Han et al. (2023) proved that accelerating RD reduces CO_2 emissions only at lower quantiles. Nonetheless, Pata et al. (2023) asserted that sustainable energy-related RD reduces CO_2 emissions, while nuclear energy-related RD has little or no effect on the quality of the environment. In addition, Herzer (2022) suggested that RD spending reduces CO_2 emissions in G7 nations. Finally, Yang et al. (2022) discovered that RD spending in G7 countries serves a similar environmentally friendly purpose. Thus, the following hypotheses are formulated.

H1. ETs positively impact GEG progress.

H2. RD spending positively contributes to GEG.

2.2.2 Financial globalization and green growth

Several studies have been conducted to explore the effects of globalization on growth and environmental quality based on some theoretical underpinnings. For instance, Shahbaz et al. (2018), Haseeb et al. (2018) and Solarin et al. (2017) all examined the effects of globalization on environmental quality and discovered a negative association between them. These studies found that globalization promotes FDI, resulting in environmental strain through resource depletion and heightened pollution, albeit alongside enhanced access to goods and services (trade). In addition, the manufacture, delivery, and consumption of commodities increase the use of fossil fuels, which is detrimental to the environment. These findings are in line with the evidence presented by Kirikkaleli et al. (2021) and Akadiri et al. (2021), who contended that the globalization of economies increases economic activity, increases energy consumption, and consequently causes ecological contamination, which has a destructive impact on environmental quality. Likewise, a study by Xia et al. (2022) indicates a strong and positive correlation between globalization and carbon emissions. Additionally, Ulucak et al. (2020) investigated the relationship between FG and the quality of the environment in developing nations and verified that FG exerts a positive impact on environmental quality.

Using the MMQR approach, Chen et al. (2023a) argued that FG significantly helps improve the environmental quality in G7 countries. Additionally, Ramzan et al. (2023) investigated the effect of FG on the sustainability of the environment and energy transition in the United Kingdom and revealed that FG hinders the energy transition. Wang et al. (2023a) found that the effects of FG on CO_2 emissions are asymmetric for some Asian economies. Moreover, Jiang & Chang (2022) revealed that FG has a positive influence on GEG, while Wang et al. (2021) reported a negative impact on industrial sector green productivity due to spillover effects.

Furthermore, FG can moderate the impacts of ETs and RD on GEG. According to the technique impact channel, FG can minimize pollutant emissions by enhancing effective and eco-friendly innovative practices and consequently accelerating GEG (Chen et al., 2023b). Moreover, ETs can promote a green revolution in the manufacturing sectors of receiving nations (Li et al., 2019). FG promotes GEG by facilitating environmental innovation and renewable energy sharing. Financial liberalization also improves the stimuli for FDI-related RD operations (Dauvergne and Lister, 2012). This view is supported by Zheng et al. (2023), who suggested that FG significantly enhances technological innovation.

FG also stimulates the linkages between financial systems and can lead host countries to adopt green manufacturing techniques and RD-led green manufacturing activities (Sbia et al., 2017). Globalization is another term for financial liberalization, and it is utilized to attract RD activity as stimulated by FDI (Chen et al., 2023a). An effective and thriving financial system delivers convenient access to a diverse range of financial goods and services, which can encourage RD tasks, improve technological advancements, and boost energy efficiency initiatives to significantly enhance the quality of the environment (Murshed, 2020). Likewise, FG provides eco-friendly and efficient innovative technologies through its technique effect, enhancing GEG.

Moreover, Li et al. (2019) contended that FG drives technological progress, hastening the transition to eco-friendly practices within host economies' industrial sectors, thereby fostering GEG. Financial freedom and liberalization attract RD endeavours from foreign investments (Chen et al., 2023b). Additionally, FG enhances the efficiency and eco-friendliness of green innovations through the technique effect, consequently bolstering green growth (Chen et al., 2023a).

Hence, the following hypotheses are articulated.

H3. *FG positively impacts GEG.*

H4. FG positively moderates the effects of ETs and RD on GEG.

2.3 Literature summary and research gap

Most empirical literature on the connection between ETs and GEG progress primarily focuses on economically advanced countries. For example, Meiling et al. (2020), Fernandes et al. (2021), Ali et al. (2023), Nosreen et al. (2021), Herzer (2022), and Yang et al. (2022) focused their investigations on advanced economies, such as OECD, G7 and EU countries, while the remaining studies are focused on a single or only a few countries. In addition, most of these studies examine the effects of ETs and RD on environmental sustainability as proxied by CO_2 emissions. Hence, most previous research has concentrated on the impact of ETs and RD on environmental sustainability. In contrast, this study offers a distinctive examination of the role of ETs and RD in promoting green growth in EMEs. Therefore, this study bridges this gap by investigating the effects of ETs on GEG in EMEs using GEG, which proxies GTFP driven by the MLPI via the directional distance function.

Moreover, most existing studies focus on the relationship between FG and carbon emissions, primarily in developed countries. Nonetheless, the empirical findings are conflicting. Some researchers argue that globalization negatively influences environmental quality, and some other scholars argue that it has a positive effect on environmental quality. For example, Kirikkaleli et al. (2021), Akadiri et al. (2021), Xia et al. (2022), and Ramzan et al. (2023) contended that globalization has a destructive impact on environmental quality, which can negatively influence progress toward GEG. Conversely, Ulucak et al. (2020) and Chen et al. (2023b) revealed that enhancing FG improves environmental quality. Therefore, this research aims to address the current research gaps and bridge conflicting findings on the effects of FG on GEG in EMEs.

Besides, the existing research has a gap in bringing the role of FG on the effects of ETs and RD on GEG. Therefore, this study bridges this gap by examining the direct effect of FG on GEG and the moderating role of FG on the effects of ETs and RD on GEG in EMEs. Besides, globalization provides ecologically beneficial technology; the quality of the environment will improve as financial interaction increases (Ahmad et al., 2021). Besides, the concept is based on the idea that FG enhances the interaction between financial channels and international firms, potentially facilitating significant technology transfer for ETs and RD to EMEs (Fan and Hao, 2020). Furthermore, a high level of complementarity exists between environmental innovation and FG (Majeed et al., 2022). FG not only supports the growth of the financial sector but also facilitates the transfer of knowledge and technology to developing nations (Tesega, 2022), thereby contributing to enhanced innovation within these countries (Zheng et al., 2023). However, the existing literature is silent on how FG moderates the role of ETs and RD on GEG in the EMEs.

Thus, this research is innovative in further building on the literature by examining this intricate connection and shedding light on the moderating effects of FG on the impact of ETs and RD on GEG in EMEs using more advanced econometric strategies.

3 Methodology and data

3.1 Directional distance function

The DDF is an example of a production function that incorporates positive and negative outcomes into the model (Xia and Xu, 2020). This technique enables the alteration of numerous outputs while leaving multiple inputs unaltered, thus increasing the feasibility of the DDF (Chung et al., 1997). Shephard, (2006) introduced the input-output distance function. In addition, Chung et al. (1997) developed a DDF based on the Shephard function to address its shortcomings. Based on these methodologies, a production possibility set (PPS) was built to account for environmental parameters when incorporating elements such as energy and the environment.

We construct the GP using the output-oriented distance function of Chung et al. (1997), which is used to examine the output disparities among decision-making units (DMUs) under identical inputs. Assume that for each DMU across time $t = 1 \ldots T$, there are N inputs $w = (w1 \ldots, wn)$, M desirable outputs $h = (h1 \ldots, hm)$, and I undesirable outputs $l = (l1 \ldots, li)$. Thus, all units of a DMU exploit a vector of inputs $w \in B_{+}^{N}$, a vector of the desired output $h \in B_{+}^{N}$, and a set of unwanted outputs $l \in B_{+}^{I}$. Then, we can characterize technologies by their product sets. All production occurs within period $t\,(1, \ldots, T)$ of the kth $(1, \ldots, k)$ decision-making unit.

$$D_0(w, h, l) = \inf\{\phi\colon\ ((h, l)/\phi) \in P(w)\} \tag{1}$$

$$P(w) = \{(h, l)\colon\ w \text{ can provide } (h, l)\} \tag{2}$$

We begin by estimating whether reducing undesired output is expensive, assuming in Eq. 3 that bad outputs are not easily disposed of. This means that decreasing undesired output is achievable only by concurrently decreasing the favourable outputs while maintaining a fixed level of inputs.

$$(h, l) \in P(w) \text{ and } 0 \le \phi \le 1 \text{ show } (\phi h, \phi l) \in P(w) \tag{3}$$

Furthermore, when an acceptable output is believed to be freely reusable, the subsequent postulate in Eq. 4 can be stated.

$$(h, l) \in P(w) \text{ and } h' \le h \text{ imply } (h', l) \in P(w) \tag{4}$$

Finally, as the desired and undesirable outputs are null-joint, we construct Eq. 5. The undesired output is an inevitable consequence of the intended outcome. Zero undesirable output equals nil desirable output.

$$f\ (h, l) \in P(w) \text{ and } h = 0 \text{ then } l = 0 \tag{5}$$

Therefore, the primary Malmquist index utilizes Shephard's distance strategy, which is defined as:

$$D_0(w, h, l) = \inf\{\phi\colon\ ((h, l)/\phi) \in P(w)\} \tag{6}$$

This function proportionally increases the desired and unwanted outputs (h,l). This strategy does not eliminate undesirables since both desired and undesired outputs increase concurrently, leading to the adjustment of the former Malmquist technique. Thus, we employ the DDF as stated in Eq. 7 to increase the desirable outputs while minimizing the unwanted outputs.

$$\vec{D}_O(w, h, l; d) = \sup\{\alpha\colon\ (h, l) + \alpha d \in P(w)\} \tag{7}$$

where "d" is the vector of "directions" in which the outputs are scaled. In our case, d=(h,–l), i.e., the desirable outputs increase, and the undesirable outputs decrease.

3.2 Input and output variables and the GEG measurement

The GP is calculated by applying the MLPI as established by Chung et al. (1997), which is subject to the DDF. Supposing $t = 1 \ldots, T$ periods, the MLPI with undesirable output is given as follows:

$$MLPI = \left[\frac{\left(1 + D_o^t\left(w^t, h^t, l^t, -l^t\right)\right) \quad \left(1 + D_o^{t+1}\left(w^t, h^t, l^t; h^t - l^t\right)\right)}{\left(1 + D_o^t\left(w^{t+1}, h^{t+1}, l^{t+1}; h^{t+1}, -l^{t+1}\right)\right)\left(1 + D_o^{t+1}\left(w^{t+1}, h^{t+1}, l^{t+1}; h^{t+1}, -l^{t+1}\right)\right)}\right]^{1/2} \tag{8}$$

The MLPI is calculated by computing the difference between time t and time t + 1. The MLPI measurement suggests that productivity increases when the values are greater than one and decreases when the values are less than one. The Malmquist–Luenberger efficiency change (ECH) and Malmquist–Luenberger technical change (TCH) are two components of this index.

$$ECH_t^{t+1} = \frac{\left(1 + D_o^t\left(w^t, h^t, l^t, -l^t\right)\right)}{\left(1 + D_o^{t+1}\left(w^{t+1}, h^{t+1}, l^{t+1}; h^{t+1}, -l^{t+1}\right)\right)} \tag{9}$$

$$TCH_t^{t+1} = \left[\frac{\left(1 + D_o^{t+1}\left(w^t, h^t, l^t, -l^t\right)\right)\left(1 + D_o^{t+1}\left(w^{t+1}, h^{t+1}, l^{t+1}; h^{t+1} - l^{t+1}\right)\right)}{\left(1 + D_o^t\left(w^t, h^t, l^t, -l^{t+1}\right)\right)\left(1 + D_o^t\left(w^{t+1}, h^{t+1}, l^{t+1}; h^{t+1}, -l^{t+1}\right)\right)}\right]^{1/2} \tag{10}$$

TCH_t^{t+1} calculates the shift in the Frontier with the geometric mean of the technical change between t and t + 1 using input vectors from the two periods. ECH_t^{t+1} shows the variation in relative efficiency between t and t + 1. These indices show that productivity increases when the values are greater than one.

Finally, according to the current research, the labor force, capital stock, and energy consumption are frequently used as inputs, and real GDP is used as the desired output; CO_2 emissions, SO_2 emissions, and wastewater are used as proxies for undesirable outputs (Kumar, 2006; Li and Lin, 2016; Sun, 2022). Considering the availability of data, we use the labor force, capital stock, and energy consumption as the inputs, real GDP as the desirable output, and CO_2 emissions as the undesirable output. We used capital stock data from the Penn World Table database. In addition, total energy consumption is used to represent energy input.

3.3 Theoretical underpinnings and model construction

Theoretically, ET aims to achieve sustainable development and pollution control to substantially reduce the environmental impact associated with economic growth (Hart, 1995). Consequently, ETs affect GEG by supporting green investments, which prioritize energy savings, assist in the transition from fossil fuels to renewable sources and reduce the level of gas emissions, thus positively contributing to the GEG of EMEs.

In addition, RD can impact GEG through various mechanisms. For example, increasing RD investments can facilitate technological advancements in the energy sector, fostering the generation of clean, green energy, which has the potential to make a substantial contribution to GEG (Lee and Min, 2015) and enhance the level of energy efficiency (Ma et al., 2022). Furthermore, RD investments can be crucial in mitigating CO_2 emissions, significantly contributing to GEG.

Following endogenous growth theory, which aimed to model investment in technological progress and RD to growth (Aghion and Howitt, 1997), the green Solow model, which incorporates abatement purpose (Brock and Taylor, 2010), modern growth theories that suggest technological innovation positively influences GEG (Acemoglu et al., 2016) and ecological modernization theory (Janicke, 2020), this study defines the expected effects of ETs and RD on GEG. Thus, based on these theoretical backgrounds, the GEG defined in Eq. 11 below is expected to be positively affected by ETs ($\alpha = \partial \ln GEG/\partial \ln ET > 0$). Likewise, the GEG is projected to be positively affected by RD ($\eta = \partial \ln GEG/\partial \ln RD > 0$). Furthermore, based on the technique effect channel of globalization, which suggests that by fostering efficient and environmentally friendly green innovations, FG has the potential to mitigate pollution emissions, thereby fostering green growth. Therefore, we propose that FG is assumed to positively affect GEG ($\theta = \partial \ln GEG/\partial \ln FG > 0$). However, the magnitude of ETs, RD and FG effects are heterogeneous across the GEG distribution.

$$\ln GEG_{it} = \beta_n{}' X_{it} + \alpha \ln ET_{it} + \eta \ln RD_{it} + \theta \ln FG_{it} + \varepsilon_{it} \tag{11}$$

GEG represents progress toward GEG as proxied by GP. X_{it} is the control variable and includes consumption, capital formation, energy consumption, the labor force and natural resources. RD_{it} is research and development spending, FG_{it} is financial globalization, and ET_{it} is environmental technology. βs, α, η and θ are parameters of coefficients, and ε denotes the stochastic term that is independently and identically distributed across individual country i at time t. t represents time in years (2000–2019), and i represents the panel of countries 1. . ..25.

Moreover, FG fosters connections between financial systems, potentially through the introduction of green manufacturing methods and RD-driven green manufacturing endeavours in host countries (Sbia et al., 2017). Therefore, FG facilitates the development of environmentally friendly and efficient innovative technologies through its technique effect, thereby amplifying GEG. According to the technique impact pathway, FG has the potential to curtail pollutant emissions by bolstering the adoption of efficient and eco-friendly innovative practices, consequently expediting the progress toward GEG (Chen et al., 2023a). Additionally, FG prompts the emergence of ETs, which in turn catalyzes the green revolution of EMEs (Li et al., 2019). Therefore, FG positively moderates and catalyzes the positive effects of ETs and RD on GEG in EMEs (for details, see Section 4.4).

$$GEG_{it} = \beta_n{}' X_{it} + \vartheta \ln ET_{it} + \eta \ln RD_{it} + \alpha \ln FG_{it} + \psi \ln FG_{it} \times \ln ET_{it} + \kappa \ln FG_{it} \times \ln RD_{it} + \varepsilon_{it} \tag{12}$$

where ψ and κ are the coefficients of the interaction terms.

3.4 Model specification

In panel data investigations, capturing the individual effects on the entire distribution, as well as outliers, to regulate and classify the conditional heterogeneous covariance effects is crucial, particularly when the error term is not normally distributed (Flores et al., 2014; Musibau et al., 2021). These issues can be captured through the use of quantile regression methods because quantile regression strategies correct the sample size bias caused by endogenous regressors (Canay, 2011) and eliminate the bias caused by distributional heterogeneity (Zhu et al., 2016). However, despite being resilient

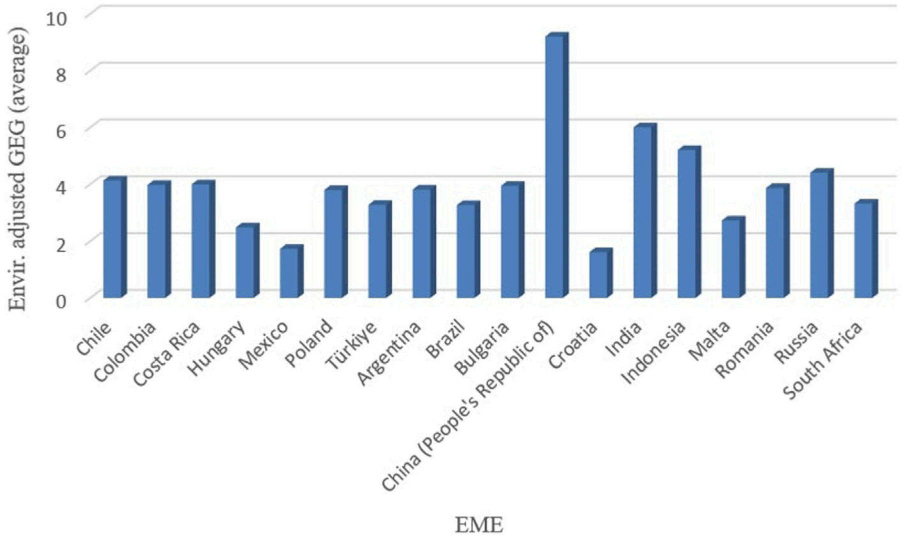

FIGURE 1
Distribution of environmentally adjusted green productivity based on OECD data.

to outliers, traditional quantile regression does not take into account any possible unobserved heterogeneity across individuals in a panel (Ike et al., 2020).

The MMQR model with fixed effects proposed by Machado and Silva (2019) represents a robust and alternative method capable of solving individual heterogeneity concerns. It produces accurate and resilient results when the dataset's distribution lacks a clear shape, contains outliers, demonstrates minimal or no correlation, and deviates from normality. It effectively discerns the unique characteristics of different quantile values, tackling challenges stemming from uneven distribution (Alhassan et al., 2020). This method is used to identify the conditional heterogeneous covariance effects of RD, ETs and FG on GEG by permitting the individual effects to influence the entire distribution, as opposed to merely altering means, as in Canay (2011). This strategy implies that the covariate variables influence the distribution of the variables of interest only through the location and scale functions and not through location shifters alone. Consequently, the MMQR estimation method is most applicable when the panel data framework contains individual effects and endogenous explanatory variables (Ike et al., 2020). It additionally offers noncrossing regression quantile estimates. Moreover, it accommodates asymmetry based on location, as the parameters may vary based on the position of the predicted variable and income inequality, and delivers reliable estimates across diverse conditions, even in non-linear models (Halidu et al., 2023).

Hence, applying the MMQR estimation technique in our study is justifiable because the progression of GEG in EMEs is quite heterogeneous (Figure 1). Additionally, the economic status of each country is reflected in its emission levels (Figure 2). Hence, conducting studies incorporating individual and distributional heterogeneity across conditional quantiles is worthwhile. We, therefore, applied the MMQR with fixed effects. The econometric model for investigating the effects of RD, ETs, and FG is defined in the following Equation.

$$\mathrm{QGEG}_{it}\left(\tau/Z_{it}\right) = \beta_n{}'X_{it} + \alpha \mathrm{lnET}_{it} + \eta \ln RD_{it} + \theta \mathrm{lnFG}_{it} + \varepsilon_{it} \quad (13)$$

where $\mathrm{QGEG}_{it}(\tau/Z_{it})$ denotes the τth conditional quantile function. Z represents all explanatory variables. The residuals are orthogonal to Z_{it} and normalized to satisfy the moment conditions described in Machado and Silva (2019). All variables are transformed to their natural logarithms, thus enabling the estimation coefficients to be interpreted in terms of their elasticities.

Equation 13 implies the following:

$$QGEG_{it}\left(\tau/Z_{it}\right) = \left(\delta_i + \alpha_i q(\tau)\right) + Z_{it}'\beta + X_{it}'\chi q(\tau) \quad (14)$$

$\delta_i(\tau) \equiv \delta_i + \alpha_i q(\tau)$ is the scalar parameter, which is indicative of the quantile-τ fixed effect for individual i. The α across individual i and the sample quantile is depicted by q(α). X is a k-vector of identified components of Z that are differentiable transformations with element l given by $X_l = X_l(Z)$, L = 1,2, . . . k. The individual effects in this method do not represent intercept shifts.

This is evaluated by addressing optimization in the manner described below:

$$\min_q \sum_i \sum_t \rho_\tau \left(\hat{R}_{it} - \left(\alpha_i + X_{it}'\chi\right)q\right) \quad (15)$$

where

$$\rho_\tau(A) = (\tau - 1)AI\{A \le 0\} + \mathrm{T}AI\{A > 0\} \quad (16)$$

Due to the marginal change in i, the parameter for a dependent variable (GEG) i might represent the marginal change in the rth conditional quantile of $\mathrm{QGEG}_{it}(\tau/Z_{it})$.

In addition, Eq. 13 is modified to include the interaction between ETs and globalization to illustrate the moderating role of FG on the impacts of RD and ETs on GEG.

$$\begin{aligned}\mathrm{QGEG}_{it}\left(\tau/Z_{it}\right) = {} & \beta_n{}'X_{it} + \alpha \mathrm{lnET}_{it} + \eta \ln RD_{it} + \theta \mathrm{lnFG}_{it} \\ & + \psi \mathrm{lnFG}_{it} \times \mathrm{lnET}_{it} + \kappa \mathrm{lnFG}_{it} \times \ln RD_{it} + \varepsilon_{it}\end{aligned} \quad (17)$$

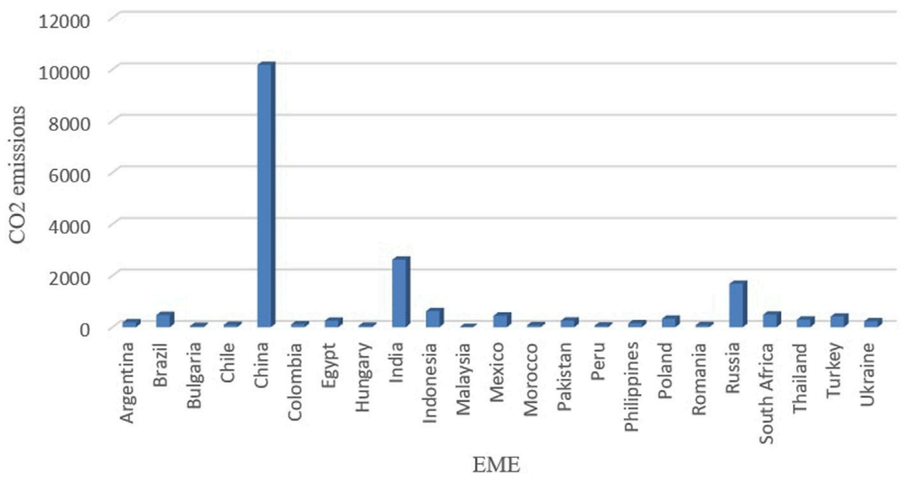

FIGURE 2
Distribution of CO_2 emissions based on Earth System Science data.

In this approach, we divide the distribution into 25th, 50th, 75th and 90th quantiles. The 25th quantile is regarded as the lower quantile, the 50th and 75th quantiles are considered the middle quantile, and the 90th quantile is considered the upper quantile.

Finally, we used the two-step system GMM, FMOLS and Tobit models for robustness purposes. The MMQR model may not solve endogeneity concerns. The two-step system GMM method recommended by Arellano and Bond, (1991) and Blundell and Bond (1998) is applied to solve potential endogeneity issues. Endogeneity issues could occur through reverse causality between GEG and any of the covariates, including our target variable. The two-step system GMM model employs lagged differences of variables as instruments for equations in levels to solve the concerns. This approach exhibits better efficiency in mitigating issues related to heteroscedasticity and autocorrelation. It employs optimal weighting matrices and characterizes each observation by its deviation from the future observations' average within the same individual while simultaneously standardizing the variance by assigning appropriate weights to each deviation (Blundell and Bond, 1998). Furthermore, it provides asymptotically precise inference with minimal statistical assumptions and employs internal instruments (Blundell and Bond, 1998). It is particularly well-suited for scenarios with a smaller time dimension than panels. Additionally, it incorporates the lagged levels of the dependent variable as instruments for equations in first differences. This approach effectively addresses the issue of endogeneity, specifically the challenge of reverse causality, thereby yielding consistent results. Moreover, the FMOLS model can provide long-term efficient estimates because it controls for the issues of cross-sectional dependency, heterogeneity and serial correlation (Özcan, 2013). These methods correct for serial correlation concerns (Özcan, 2013), provide trustworthy estimates and address concerns regarding cross-sectional dependency and heterogeneity issues (Zafar et al., 2020). In addition, the FMOLS approach has become popular because it accounts for bias and endogeneity concerns in small samples (Zafar et al., 2020). Therefore, following Zafar et al., 2020, we use the FMOLS estimator to examine the long-term role of globalization, ETs and RD on GEG in EMEs. The compelling evidence allows us to employ FMOLS to validate the long-term association among the suggested variables. Panel FMOLS offers several advantages, accommodating serial correlation, addressing endogeneity and accounting for cross-sectional heterogeneity. Additionally, it provides insights from both within and between dimensions (Erdal and Erdal, 2020). Research design, including methods of analysis and findings framework, is reported in Supplementary Figure SA2.

3.5 Data

In light of the data, we utilize 25 EMEs covering the 2000–2019 period, depending on IMF classifications[1]. This study period is delimited to 2000–2019 due to the lack of updated data available on the stock of capital since 2019 in the Penn World Table Database. The rationale for variables is based on the existing theoretical and empirical literature. The data for all variables have been collected from the most commonly used and reliable secondary sources such as the WDI of the World Bank, OECD, UNESCO, KOF Globalization Index and Our World in Data. These sources are widely used to utilize secondary data. Details of each variable have been discussed in the following sections and Supplementary Table SA1.

3.5.1 Dependent variable

We utilize the green productivity index for GEG. GEG is derived by employing the MLPI. To calculate GEG, we utilized the labor

1 List of emerging economies: Argentina, Brazil, Bulgaria, Chile, China PR, Colombia, Egypt, Georgia, Hungary, India, Indonesia, Malaysia, Mexico, Morocco, Pakistan, Peru, Philippines, Poland, Romania, Russian Federation, Saudi Arabia, South Africa, Thailand, Turkey and Ukraine.

force, stock of capital, and energy consumption as inputs, GDP in real terms as desired output, and CO_2 emissions as unwanted outputs. The real GDP and labor force were taken from the WDI database. We used capital stock data borrowed from the Penn World Table Database. Capital stock data is preferable to calculate capital from gross fixed capital formation. We utilized the energy consumption data that were provided by Our World in Data from the BP Statistical Review of World Energy. Finally, CO_2 emission data were gathered from the Earth System Science database. We repeated the exercise using CO_2 emissions as a dependent variable as a sensitivity analysis.

3.5.2 Target variables

Environmental technologies: Most of the available literature uses the number of patents to estimate ETs since patents are important indicators of a nation's innovative capacity. According to the studies of Fernandes et al. (2021) and Hussain et al. (2022), ET is represented by the number of patents connected to ET development in the OECD database. The choice of patents connected to ET stems from the increasing significance of advancing green technologies, which are intricately tied to environmental policies (Urbaniec et al., 2021).

Research and development: We used RD expenditures as complied by Our World in Data from the UNESCO database as a percentage of GDP. This measure includes the current and capital on basic, applied and experimental research. Data on expenditure for RD is preferred to show the public resources that economies invest in research on the environmental aspects of the economy. We used linear interpolation to estimate some missing values in the data. We employed RD spending to represent RD following the works of Alvarado et al. (2021).

Financial globalization: This study uses a new FG index, as Gygli et al. (2019) suggested, rather than the conventional one. Using data for the FG index from Gygli et al. (2019), available from The KOF Globalization Index website, is more robust to represent FG. In line with the findings of authors such as Nasreen et al. (2020) and Ulucak et al. (2020), we propose that FG is a critical component of environmental sustainability that favourably affects GEG. However, most extant studies have employed FDI, trade openness or composite indices as indicators of globalization.

3.5.3 Control variables

Gross fixed capital formation, total final consumption expenditure, primary energy consumption, labor force and natural resources are included as control variables following the methods of Borojo et al. (2023) and Liu et al. (2022). The gross fixed capital formation and total consumption expenditure data are collected from the World Bank database. The energy consumption data were compiled by Our World in Data from the BP Statistical Review of World Energy and Shift Energy Data Portal. These data came from the regression presented in a study by Hussain et al. (2022). Energy consumption represents the total energy consumption. The definitions of the variables and sources of data are given in Supplementary Table SA1. Additionally, the correlation coefficients of the variables are reported in Supplementary Table SA2. The summary statistics of the variables are given in Table 1 below.

TABLE 1 Summary statistics of the variables.

Variable	Obs	Mean	Std. Dev	Min	Max
$GEG_{i,t}$	500	1.035	0.324	0.277	2.225
$LogC_{i,t}$	500	4.304	0.144	3.797	4.587
$LogK_{i,t}$	499	24.921	1.283	21.519	29.441
$LogE_{i,t}$	500	1.285	0.616	0.000	2.480
$Logl_{i,t}$	500	17.137	1.246	15.009	20.475
$LogN_{i,t}$	474	0.091	0.393	−0.670	2.121
$LogET_{i,t}$	500	7.497	1.724	0.000	13.289
$LogRD_{i,t}$	481	0.613	0.413	0.042	2.245
$LogFG_{i,t}$	500	3.993	0.256	3.220	4.499

TABLE 2 Cross-section and Stationarity tests.

	Stationarity		CD-test
Variables	I (0)	I (1)	CD-test
GEG_{it}	−1.218	−13.296***	24.641***
$LogC_{i,t}$	−1.034	−1.943**	21.955***
$LogK_{i,t}$	1.138	−13.673***	13.804***
$LogE_{i,t}$	2.069	−17.556***	89.921***
$LogL_{i,t}$	0.374	8.855***	12.367***
$LogN_{i,t}$	0.404	−10.202***	8.769***
$LogET_{i,t}$	3.613	−14.416***	6.169***
$LogRD_{i,t}$	−2.000	−16.00***	7.361***
$LogFG_{i,t}$	2.435	−16.868***	79.613***

*** indicates significance at the 1% level. Lags are selected according to the AIC.

4 Results and discussion

This section provides test results, regression analysis and findings. Supplementary Figure SA2 A provides a detailed presentation of the data analysis process.

4.1 The panel unit root and cross-section independence tests

The cross-sectionally augmented IPS method of Pesaran (2007) is used to test the unit root. The results show that all the other variables are stationary at the first difference. In addition, the dependent variable, GEG, is stationary at I (1). Moreover, we determined if there was cross-sectional dependence in the dataset using the cross-sectional dependence test. The result demonstrates that EMEs have a strong economic connection, as cross-sectional independence is not accepted (Table 2).

TABLE 3 Kao cointegration test.

Kao	(I)
Modified Dickey-Fuller (D.-F.)t	−6.301***
D.-F. t	−8.189***
Augmented D.-F. t	−5.114***
Unadju. modified D.-F	−13.784***
Unadju. D.-F. t	−10.586***

*** indicates significance at the 1% level.

4.2 Cointegration test

Several methods have been devised for testing the cointegration of a set of variables. The cointegration connection is studied through a variety of methodologies, such as Westerlund (2007), Pedroni (1999), and Kao (1999). Therefore, we applied these methods in our research. Kao's (1999) cointegration test considers the intercepts of cross-sections and homogenous coefficients on the first step of regression. This method requires the intercept to be heterogeneous across cross-sections and the slope coefficients to be homogenous. Kao's cointegration test results indicate that the null hypothesis is rejected (Table 3).

4.3 The effects of RD, ETs and FG on green growth

The results of the MMQR estimator are presented in Table 4.

These findings imply that capital formation and the labor force have statistically robust positive effects on GEG in all quantiles aside from the nonsignificant effect of the labor force that occurs in the 90th quantile. Similarly, the coefficients of consumption expenditure that are used to proxy for fiscal policy measures are robustly positive in the lower and middle quantiles ($Q_{.25}$ and $Q_{.5}$), inferring that an increase in consumption expenditure improves the GEG in countries with lower levels of GEG progress. In addition, the effects of natural resources are weakly positive. However, the estimates of total energy consumption show that total energy consumption has a significant negative effect on GEG in all quantiles aside from 90th quantile, denoting that an intensification in energy consumption (nonrenewable) negatively affects the GEG of EMEs. These results are not surprising given the extremely low diversity of energy sources in EMEs, where fossil fuels generally dominate (Capozza and Samson, 2019). Moreover, these findings support existing empirical studies, such as those of Adebayo et al. (2022), Wu et al. (2022), Hussain et al. (2022) and Wang et al. (2023b), that have revealed mitigating emission effects of renewable energy consumption.

Concerning the target, the coefficients of ETs are positive and statistically significant across all quantiles. Therefore, ETs have a statistically significant beneficial effect on GEG, suggesting that ETs encourage development toward GEG in EME countries. However, the effect of ETs decreases from lower quantiles to higher quantiles, indicating that improvements in ETs in countries with lower GP levels have greater effects on GEG. Therefore, ETs serve as an important determining factor in promoting the GEG of EMEs. This may be because technological innovations can spur green technological progress, enhance resource allocation, and positively affect GEG. In other words, by developing eco-friendly green technologies, firms in EMEs can reduce energy consumption and pollution emissions, enabling green production to enhance green growth. Additionally, green innovation and technologies help in the reutilization of production waste and recycling (Zhang et al., 2018), which can positively contribute to GEG in EMEs. These outcomes are comparable with the findings of Sohag et al. (2019), Jason and Giorgos (2020), Meiling et al. (2020), Wang et al. (2018), Liu and Xin (2019) and Obobisa et al. (2022), confirming that technological progress and ETs positively impact GEG and sustainable development. Furthermore, by developing eco-friendly green technologies, EMEs can reduce their energy consumption and pollution emissions, thus enabling green production to enhance GEG. Additionally, ETs help in the reutilization of production waste and recycling (Zhao et al., 2021).

Moreover, the results of this study support the use of ecological modernization theory frameworks, the Green Solow model and

TABLE 4 The impacts of ETs, RD and FG on GEG.

Variables	Location	Scale	25th	50th	75th	90th
$LogC_{i,t}$	0.082* (0.043)	−0.082*** (0.028)	0.151*** (0.044)	0.091** (0.043)	0.018 (0.053)	−0.068 (0.074)
$LogK_{i,t}$	0.031*** (0.009)	0.004 (0.006)	0.028*** (0.009)	0.030*** (0.009)	0.033*** (0.011)	0.037** (0.015)
$LogE_{i,t}$	−0.027*** (0.008)	0.004 (0.005)	−0.030*** (0.009)	−0.027*** (0.008)	−0.024** (0.010)	−0.020 (0.014)
$logL_{i,t}$	0.023*** (0.005)	−0.006* (0.003)	0.028*** (0.006)	0.024*** (0.005)	0.019*** (0.007)	0.012 (0.009)
$logN_{i,t}$	0.024* (0.014)	0.008 (0.009)	0.017 (0.014)	0.023* (0.013)	0.030* (0.017)	0.039* (0.023)
$LogET_{i,t}$	0.126*** (0.008)	−0.020*** (0.005)	0.142*** (0.009)	0.128*** (0.008)	0.110*** (0.011)	0.090*** (0.015)
$LogRD_{i,t}$	0.129*** (0.022)	−0.019 (0.014)	0.145*** (0.022)	0.131*** (0.022)	0.114*** (0.027)	0.094** (0.038)
$LogFG_{i,t}$	0.150*** (0.021)	0.034** (0.013)	0.122*** (0.021)	0.146*** (0.020)	0.177*** (0.026)	0.212*** (0.036)
_cons	−1.996*** (0.326)	0.630*** (0.210)	−2.520*** (0.331)	−2.066*** (0.322)	−1.503*** (0.402)	−0.852 (0.561)
Obs	455	455	455	455	455	455

***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively; std. errors are displayed in brackets, i = 1, . . . ,25.

extended endogenous growth theory, which argues that promoting environmental-related innovation promotes GEG by advocating for investments that not only yield economic benefits but also enhance the broader goal of environmental sustainability (Aghion and Howitt, 1997; Brock and Taylor, 2010; Jänicke, 2020).

Furthermore, the effects of RD on GEG are positive and statistically significant across all quantiles ($Q_{.25}$ to $Q_{.9}$). The magnitude of the coefficients of RD decreases from lower quantiles to higher quantiles, implying that RD investment is more important for EMEs exhibiting less GEG progress. Thus, the results verify that increasing the share of RD spending promotes GEG in EMEs. This finding is driven by the notion that investing in RD is a crucial means of shifting the economic structure from a predominance of fossilized energy towards renewable energy sources, thereby assisting EMEs in achieving their carbon neutrality goals and GEG targets. In other words, RD contributes to the improved utilization of resources, slows the growth of pollutants associated with energy and other resource consumption, and constrains economic expansion while driving GEG in EMEs. Similarly, RD spending is anticipated to decrease the reliance of EMEs on fossil fuels, encourage the adoption of renewable energy, and increase investment in ETs. Our findings are in line with the justifications of the studies by Kihombo et al. (2021), Petrović and Lobanov (2020b), Han et al. (2023) and Herzer (2022), who argued that RD investment positively contributes to CO2 mitigation and thus contributes to GEG.

Theoretically, the results corroborate the endogenous growth theory, which posits that RD is a pivotal catalyst for economic expansion, with investments in RD yielding enduring enhancements in productivity (Brock and Taylor, 2010). Thus, within the framework of GEG, directing RD investments toward creating eco-friendly technologies can ignite innovation, enhance resource utilization, and mitigate environmental repercussions, thereby nurturing GEG's progress.

Furthermore, FG positively affects GEG in all quantiles, indicating that FG robustly enhances the progression toward GEG in the EMEs. Additionally, the magnitude of the estimates of FG increases from the lower quartile to the higher quantile ($Q_{.25}$-$Q_{.9}$), implying that FG has a greater positive impact on the GEG of countries that already exhibit a high level of GEG. These results can be used to explain why FGs encourage firms to use environmentally favourable manufacturing practices, which results in environmental quality and contributes to GEG. The positive link between FG and GEG is also based on the pollution halo hypothesis and technical effect, which provides evidence that FG improves the environment through the transfer of effective management techniques and through financial and technological spillover and transfer (Sbia et al., 2014). These findings are congruent with those of Huang et al. (2021), Sbia et al. (2014), Xia et al. (2022), Chen et al. (2023a) and Dauvergne and Lister (2012), who all reported positive associations among environmental quality, green growth and FG.

4.4 The moderating role of FG in the impacts of ETs and RD on GEG

Table 5 provides the moderating effects of FG on the effects of ETs and RD on GEG. The coefficients of the interaction terms are positive and statistically significant in all quantiles.

To determine the marginal effects of ETs and RD on GEG under FG in greater detail, the partial derivative of GEG is conditional on FG. The marginal effect of the improvement in FG to the average level in the sample can be calculated using the partial derivative Formula below:

$$\partial \mathrm{logGG}_{i,t} \big/ \partial FG_{i,t} = \hat{\beta} + \hat{\alpha} \mathrm{logFG}_{i,t} \tag{18}$$

where $\hat{\beta}$ denotes the effect of a percent increase in ETs and RD on GEG when FG is equivalent to zero and $\hat{\alpha}$ represents the coefficient of the interaction term when FG is greater than zero.

For example, the marginal effect is calculated using the first quantile (Q.25) of the MMQR estimates displayed in Table 5 and the average of the natural logarithm of FG (Table 1). Thus, at the minimum FG in the natural logarithm (3.220), the marginal effect of ETs on GEG as conditioned on FG is 0.126+ (0.066*3.220) = 0.338. Nevertheless, the conditional marginal impact of ETs on GEG subject to an approximately average FG according to the natural logarithm (3.993) is 0.126+ (0.066* 3.993) = 0.390. These results, therefore, indicate that the positive effect of ETs is increasing with respect to FG, implying that the openness of countries to FG promotes the positive effect of ETs on GEG. Similarly, at the minimum FG in the natural logarithm, the marginal effect of RD on GEG as conditioned on FG is 0.149+ (0.058*3.220) = 0.336. Nevertheless, the conditional marginal impact of ETs on GEG as subject to the approximately average natural logarithm of FG is 0.149+ (0.058* 3.993) = 0.381, implying that the beneficial effect of RD on GEG increases under FG.

Based on the theoretical framework, our findings align with the technique effect mechanism of globalization. This suggests that by promoting efficient and environmentally friendly green innovation, FG can potentially decrease pollution emissions, thus enhancing GEG.

In addition, our findings are congruent with those of Chen et al. (2023b), Li et al. (2019) and Sbia et al. (2017), who argued that FG stimulates connections between financial systems that could bring about green manufacturing techniques and RD that may encourage clean production activities and easy access to a vast array of financial goods and services that can help encourage RD operations, improve technological innovations, and improve GEG.

Therefore, FG enables the movement of capital across international borders, providing EMEs access to funds from global markets, implying that with greater financial resources available, firms in EMEs may allocate more funding towards projects focused on ETs and RD, driven by the desire to seize opportunities for innovation and competitiveness in the global marketplace. Also, FG, marked by liberalization and digital financial inclusion, enhances the allure of RD, bolstering green growth (Chen et al., 2023b).

5 Robustness test

There is reverse causality between GEG progress and ETs and RD. Therefore, we re-examined the impacts of ETs, RD and FG on GEG using a two-step system GMM model to control for potential endogeneity. The results are reported in Supplementary Table SA4. These findings support the baseline results reported in Tables 4, 5.

Additionally, we investigated the effects of FG, RD and ETs using the FMOLS and Tobit models to perform further sensitivity

TABLE 5 The moderating role of FG on the impacts of ETs and RD on GEG.

Panel I: The moderating role of FG in the impact of ETs on GEG.						
Variables	Location	Scale	25th	50th	75th	90th
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
$LogET_{i,t}$	0.117*** (0.007)	−0.011** (0.004)	0.126*** (0.006)	0.119*** (0.006)	0.109*** (0.008)	0.098*** (0.011)
$LogRD_{i,t}$	0.135*** (0.019)	−0.020* (0.012)	0.153*** (0.018)	0.139*** (0.018)	0.119*** (0.024)	0.099*** (0.033)
$LogFG_{i,t}$	0.123*** (0.019)	0.022* (0.012)	0.103*** (0.019)	0.119*** (0.019)	0.139*** (0.024)	0.161*** (0.033)
$LogET_{i,t}$* $LogFG_{i,t}$	0.060*** (0.011)	−0.007 (0.007)	0.066*** (0.010)	0.061*** (0.010)	0.054*** (0.013)	0.046** (0.018)
Panel II: The moderating role of FG in the impact of RD on GEG.						
Variables	Location	Scale	25th	50th	75th	90th
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
$LogET_{i,t}$	0.120*** (0.007)	−0.014*** (0.004)	0.132*** (0.007)	0.122*** (0.007)	0.110*** (0.009)	0.096*** (0.012)
$LogRD_{i,t}$	0.128*** (0.019)	−0.024** (0.012)	0.149*** (0.018)	0.132*** (0.018)	0.110*** (0.024)	0.086** (0.033)
$LogFG_{i,t}$	0.025 (0.030)	0.064*** (0.019)	−0.032 (0.029)	0.013 (0.029)	0.073* (0.039)	0.138** (0.053)
$LogRD_{i,t}$* $LogFG_{i,t}$	0.047*** (0.008)	−0.012** (0.005)	0.058*** (0.008)	0.050*** (0.008)	0.038*** (0.011)	0.026* (0.015)
Obs	455	455	455	455	455	455

***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively; std. errors are displayed in brackets, i = 1, . . . ,25.

analysis. The findings are consistent with the baseline results. RD and ETs have a beneficial impact on GEG, showing that RD and ETs promote GEG. In addition, FG positively contributed to GEG (Supplementary Table SA5; Supplementary Table SA6). These results further confirm that the magnitudes of the interaction terms are positive and statistically significant. Finally, we investigated the effects of RD, ETs and FD on CO_2 emissions and the results are reported in Supplementary Table SA3.

6 Conclusion and policy implications

This study contributes to the current GEG literature by offering novel evidence on the impacts of ETs, RD and FG on GEG in 25 EMEs using data covering the period from 2000 to 2019. We extend the analysis to further investigate the moderating role of FG on the effects of ETs and RD on GEG. We drive the proxy to GEG using the DDF MLPI strategy. This study applies the MMQR with a fixed effects model that can capture distributional heterogeneity, nonnormality, endogeneity, and outlier concerns. It is a robust and alternative method capable of solving individual heterogeneity concerns. The two-step system GMM, FMOLS and Tobit models are also used for robustness purposes. The two-step system GMM method is applied to solve potential endogeneity issues. The FMOLS model is used to get efficient findings because it solves heterogeneity and serial correlation concerns.

The findings imply that ETs have a robust positive impact on GEG, showing evidence that ETs promote GEG advancement in all quantiles ($Q_{.25}$, $Q_{.5}$, $Q_{.75}$ and $Q_{.9}$). In addition, the effect of ETs decreases from lower quantiles to higher quantiles, indicating that improvements in ETs in countries with lower levels of GEG have greater effects on GEG progress in EMEs. Thus, green technical progress can be generated, efficiency can be increased, and the allocation rate of resources in EMEs can be improved, thereby contributing to GEG.

In addition, the impacts of RD on GEG are positive and statistically significant in all quantiles ($Q_{.25}$ to $Q_{.9}$). Compared to that of ETs, the magnitude of the RD coefficient decreases from lower quantiles to higher quantiles, indicating that RD spending is crucial for EMEs with less advanced GEG. Consequently, the findings confirm that boosting the proportion of RD expenditures advances GEG in EMEs. In addition, FG had a positive impact on GEG, indicating that FG promotes GEG progress in EMEs in all quantiles ($Q_{.25}$, $Q_{.5}$, $Q_{.75}$ and $Q_{.9}$).

In addition, the magnitude of the coefficient of FG decreases from the lower quartile to the higher quantile ($Q_{.25}$-$Q_{.9}$), revealing that FG has a greater positive impact on GEG in countries with higher GP. These results further imply that the positive influence of ETs and RD on GEG is greater after controlling for the moderating role of FG, implying that EMEs the openness of EMEs to FG promotes ETs and RD and, in turn, drives GEG. In other words, the influence of FG on advancement toward GEG in EMEs can be facilitated through policy measures and planning that promote ETs through the development of novel innovations and economic frameworks that improve the environment and advances in technology in energy preservation, effectiveness and prevention of pollution. Thus, our findings align with the technique effect channel, which posits that FG can reduce pollutant emissions by promoting sustainable and eco-friendly green innovation, hence intensifying GEG. Therefore, FG increases efficient and eco-friendly green innovations via the technique effect, improving GEG. Moreover, our results show that FG positively influences the RD-GEG nexus in EMEs, which infers that FG enhances the incentives for RD activities related to FDI and capital inflow into EMEs. Hence, FG can provide easier access to capital for EMEs to invest in ETs and finance RD, thereby facilitating GEG.

This research provides substantial theoretical contributions by offering insights into the impact of diverse strategies for adopting ETs and varying degrees of RD investment on achieving GEG in various EMEs. In this regard, the findings support the theoretical views of ecological modernization, the green Solow model and endogenous growth theory that claim investments in green innovation and RD can shift the growth path to more environmentally friendly. Besides, the results of this research support the technique effect channel of globalization, believing that by fostering efficient and environmentally friendly green innovations, FG has the potential to foster green growth.

Additionally, by exploring how FG moderates these connections, this study enhances theoretical comprehension by emphasizing the intricate nature of global financial integration in fostering environmentally sustainable economic development in EMEs. In addition, achieving a balance among these elements is crucial for establishing environments conducive to driving sustainable development in emerging economies. Thus, our results support the theoretical prediction that FG increases efficient and eco-friendly green innovations via the technique effect, thereby improving GEG.

From a practical perspective, the study can offer policymakers, businesses, and other stakeholders in EMEs actionable insights and evidence-based recommendations. By understanding the specific impacts of ETs, RD, and FG on GEG in their respective contexts, decision-makers can formulate more effective policies and strategies to promote GEG. More specifically, the findings of this study shed new light on the implications of the literature and can advance some beneficial contributions to scholars, policymakers, and governments, as discussed below.

First, to speed up GEG development, policymakers and governments in EMEs should implement ETs-friendly policies and plans. The findings can guide governments and investors, helping them decide how to allocate their investments towards sustainable development projects. For example, to attain environmental sustainability goals (SDG-13) and growth central to the GEG, EMEs need to encourage ETs to promote innovation (SDG-9). Therefore, EMEs should promote FG to enable the movement of capital across borders, fostering greater investment in sustainable projects and technologies designed to address climate change. This encompasses funding for initiatives such as renewable energy, energy efficiency, and other environmentally friendly endeavours. In other words, in the framework of sustainable growth, policymakers in EMEs must ensure that green innovation and technology can resolve current economic and ecological challenges and provide decent employment opportunities, which can, in turn, contribute to achieving GEG. Thus, EMEs should advocate for adopting ETs that improve resource efficiency and promote sustainable practices, aligning with the responsible consumption and production goals outlined in SDG-8.

Second, the development of cautious strategies to promote technologically innovative businesses is crucial for advancing GEG in EMEs. In this respect, a relatively larger proportion of green credit and incentives should be allocated to firms and industries that prioritize green innovation and those environmentally friendly, greener industries that are committed to promoting industrialization and economic growth while maintaining environmental quality. Consequently, providing green financing through issuing green bonds and green credits and subsidizing companies that invest in eco-friendly innovation is crucial for facilitating the GEG of EMEs. Also, setting regulations such as emission standards and renewable energy targets will promote ETs in EMEs that can boost the progress of GEG.

Third, regarding the FG, EMEs should focus on financial liberalization and establish a political framework to entice more foreign capital by promoting FG. In turn, financial capital flow results in using novel manufacturing methods and acquiring advanced technologies that are more energy-efficient and environmentally benign, thereby promoting GEG in EMEs.

Fourth, the practical roles of ETs and RD can be integrated within FG frameworks to promote GEG in EMEs. This includes designing policies that encourage the adoption of environmentally friendly technologies while leveraging FG to attract investment in green projects to promote GEG. In this regard, FG can facilitate the transfer of ETs by providing the necessary funding for technology acquisition and implementation. FG stimulates cooperation among financial channels and attracts capital with the technological and financial capabilities to transmit ETs and RD to EMEs. Therefore, EMEs should develop targeted policies to promote FG so that spillovers from capital inflows from various countries can promote GEG by providing the financial capacity to address the financial constraints of EMEs regarding conducting RD and investing in ETs.

Finally, the findings of this research show that increasing RD spending is important for GEG and, therefore, investments in RD projects should be increased and sufficient financial rewards for undertaking meaningful research activities should be provided in EMEs. Also, For RD to impact GEG, EME governments should stimulate private sector investment in areas that include environmental welfare-related technology development, energy efficiency, and energy transition.

This study is limited by the availability of data on EMEs. Thus, future research should extend and perform similar studies in the context of a wide range of developing countries.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: WDI database, Our World in Data, OECD database and UNESCO database.

Author contributions

DB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1351861/full#supplementary-material

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