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Assessing the Role of Digital Economy Transformation in Achieving Green Growth: Insights from Novel Green Growth and Digital Economy Indices

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Abstract

The global temperature is rising, and economies need to take stringent measures to keep it below the 1.5 °C limit set by COP28. For this purpose, global economies need to take strategic measures to reduce pollution levels. The researchers and environmentalists suggest that global economies adopt a long-term, sustainable growth strategy, for instance, green growth (GG). Thus, the digital economy (DE) is a vital solution for promoting the GG through innovation and sustainable practices. The DE plays a significant role in achieving the various Sustainable Development Goals (SDGs) for the economy. Thus, the present study develops the comprehensive indices for the GG and DE. The study uses panel data from 2000 to 2022 for empirical analysis across 104 global economies, employing two novel econometric techniques: the method of moments quantile regression (MMQR) and the system generalised method of moments (GMM). The outcome found a significant positive impact of DE on global GG across the lower, medium, and higher quantiles. Interestingly, low-income economies exhibit a higher quantile value for the DE than high-income economies. The findings also highlight the positive influence of trade, general government expenditures and ecological taxes on GG, while urbanization shows a negative association. Further, the outcome from the GMM system is consistent with the MMQR, which shows that the DE has a significant and positive effect on global GG. This study proposes a phased policy framework to achieve SDGs 8 and 13 based on these results.

Keywords Digital Economy, Green Growth, Ecological Taxes, MMQR, Global Economies

1. Introduction

Global economies (GE) have experienced rapid climate change over the last few decades, and 2023 was recorded as the hottest year since the preindustrial era. Over the past decade, GE has faced severe environmental threats, and temperatures have been around 1.8 °C above preindustrial levels, highlighting the alarming situation. This increasing trend in temperature poses various environmental challenges for the planet, mainly affecting wildlife and human life, as well as forestry and agricultural activities (NOAA, 2024). In addition, it increases the problem of heat strokes, anxiety, and various diseases, i.e., diarrhoea, lung infection, and undernourishment (UNEP, 2023). The World Health Organisation (2023) report indicates that this extreme weather event is responsible for heat stress and undernutrition and may cause approximately 250000 more deaths. Thus, the conventional output growth of the GE adversely affected the environment by increasing carbon emissions (CEs) (Green Policy Platform, 2024). It significantly affects the quality of the environment and future growth opportunities. Thus, the researchers and environmentalists have emphasised to GE that it 69adopt a sustainable output growth model, particularly the GG strategy. It promotes sustainable output growth and helps economies achieve the SDGs, for instance, SDGs 8 and 9, which address decent work and economic growth and climate action.

Another report by the World Bank (2012) defines the GG strategy as promoting sustainable output growth while preserving the environment and focusing on innovation and social equity across economies. This definition emphasises the three main elements of GG, namely environmental sustainability, socioeconomic sustainability, and green economic opportunities. So, the purpose of GG is to enhance social equity by creating new green jobs and protecting the environment from further deterioration through technological innovations, sustainable practices, and implementing strategic ecological measures. The study by Cheba et al. (2022) highlights that European economies adopted the GG strategy earlier and reaped greater benefits than other regions. This study indicates that GG had 1.6% of GDP in 2000 and rose to about 2.2% in 2017. It shows the increasing trend of GG over time. These economies achieve higher economic returns, create more green jobs, and promote sustainable development while reducing CEs, thereby improving environmental quality across the European region. Similarly, the Green Policy Platform (2024) emphasises that the GG is the key strategy to meet the rising needs, i.e., energy, food and water, as the expected 9 billion population around the globe by 2050. Due to these severe challenges, GG helps to create new markets and investment opportunities in green technologies, adding more jobs, reducing environmental impacts, and building resilience against economic and climate shocks (Paul & Weinthal, 2019).

World environmental organisations such as UNEP (2012), OECD (2024), and the World Bank (2024) focus on promoting the DE. it fosters the pace of innovations, efficiency, transparency, and socioeconomic inclusion around the GE. These organisations define the DE as including digital tools that enhance network coverage and internet connectivity, support online banking, enable buying and selling of goods while staying at home or at the office, and promote the e-government systems. This definition elaborates on how DE enhances digital infrastructure and innovation, promotes sustainable output growth, and alters trade patterns around the GE. Thus, the DE consists of digital services, online platforms, and products that play a key role in stimulating sustainable output growth while emitting fewer CEs, thereby improving environmental performance. Furthermore, the studies by Gu et al. (2024) and Dahlman et al. (2016) found that DE is the primary pillar of output growth after industrial and agricultural economies. Another study by Liao (2023) indicates that DE is an essential part of GG and contributes 15% of global GDP. In addition, China is a global leader in promoting the DE; its share rose from 14.5% in 2005 to about 39.8% in 2021. On the other hand, other economies such as South Korea, the UK and India contribute approximately 30%, 12.4%, and13.42%, respectively[1].

In recent years, digital technologies (DT) and the internet have reshaped the lives of individuals, businesses, government systems, and the manufacturing sector worldwide. Further, DT plays a significant role in promoting sustainable output growth through digital transformation, accelerating the pace of innovation, reducing travel and transaction costs, and providing easy access to information and communication systems across the various sectors of the economy (Bahia et al., 2020; Herman & Oliver, 2023; Jensen et al., 2023). It provides remote job opportunities to skilled individuals around the globe, leading to increased consumption and green investment and simultaneously boosting the welfare of economies (Bowen, 2012; Chiplunkar & Goldberg, 2022). Moreover, DT enables businesses and public sectors to monitor economic activities and make instant decisions. It helps mitigate policy uncertainty, ultimately reducing inefficiency, stimulating innovation, enhancing sustainable development, and opening the door to new markets worldwide (Verdes et al., 2022; Gomes et al., 2022; Lao et al., 2022). DT across sectors of the economy stimulates accountability and transparency, enhances the effectiveness of ecological policies and strategies, and strengthens environmental governance and public participation services (Verdes et al., 2022; Chiplunkar & Goldberg, 2022). Additionally, DT can effectively change the education and learning system. It promotes the e-learning system, enabling students who cannot afford school fees and travel

[1] https://www.idc-a.org/download?source=Global%20Digital%20Economy%20Report%20-%202025&insight=qUi9XgvyrzSkyDUy9Tqr

costs to access the digital classroom (Nwankwo, 2018). Besides, it promotes online banking, easy access to credit, an instant payment system without hurdles, and savings that can accelerate sustainable development worldwide (Chandra et al., 2024).

In addition, the recent study by Majeed and Sharif (2024) uses GG as a proxy for GDP after adjusting for pollution emissions, and measures DE using only four indicators: fixed telephone subscribers, mobile phone users, fixed broadband, and net users. The study findings demonstrate that DE improves the level of GG across the global economies. Similarly, another study by Liu et al. (2024) developed the DE index based on five indicators: mobile users, internet coverage, employees in the information industry, and digital finance. The findings highlight that DE promotes sustainable output growth. On the other hand, Lee et al. (2024) measure DE using five indicators to analyse its influence on green economic efficiency. The findings suggest that DE significantly improves green efficiency. Noelia (2022) constructed the DE index based on six dimensions: digital infrastructure, affordability, adoption, and government regulations. The findings highlight that digital transformation boosts global economic growth. However, the preceding studies use limited sets of DE and GG indicators, examine different regions, and employ various estimation methods.

Thus, past studies have constructed the index using limited indicators, especially net coverage, internet users, and broadband subscriptions. Further, previous studies failed to cover essential indicators such as digital finance, social support, green employment, and green innovation. Similarly, a number of studies in past literature have measured GG as a composite of a few indicators or used a proxy for the GG. In empirical estimation, past studies use connectional econometric techniques such as Panel ARDL, FMOLS, dynamic OLS, and PGM. These techniques cannot capture outliers in the data or address endogeneity issues. To address these shortcomings, the present study constructs comprehensive indices for both DE and GG. It uses novel econometric methods, i.e., MMQR and Two-step GMM, which can handle large samples, address data outliers, and capture endogeneity, yielding robust results. The purpose of the present study is to investigate the linkage between DE and GG based on a panel of GE. The preceding discussion highlights the importance of digital transformation, and economies are sharply moving toward digitalization. These DTs significantly promote innovation and sustainable output growth and, simultaneously, help economies achieve various SDGs. Hence, the current study empirically examines whether the DE stimulates the GG across the GE and offers relevant recommendations and policy strategies for environmental researchers and government bodies to foster GG levels. Thus, upon prior arguments, the recent study asserts that a digital economy, with government expenditures, trade, and ecological taxes, could significantly influence GG. Consequently, the study poses the following research question:

Research Question: How does the digital economy, along with government expenditures, trade openness, and ecological taxes, affect green growth?

In order to explore the above research question, the current study contributes to the existing body of literature in the following ways:

1. There are several studies that explore the determinants of GG while deploying various proxies in order to measure the GG. Since most pertinent studies rely on a single proxy variable to measure GG. However, the GG is a broader concept, so single-variable-based proxies might be biased in measuring GG. To address this bias in GG measurement, the recent study develops a comprehensive GG Index to more accurately assess GG rather than relying on a single proxy variable. This index is based on three dimensions: socioeconomic sustainability (SOSB) , environmental sustainability (ES), and green economic opportunities (GEOP). Each dimension includes multiple variables: SOSB has three sub-dimensions and 14 indicators, ES has four sub-dimensions and 14 indicators, and GEOP has four indicators. This index provides a robust framework for capturing green growth impacts, allowing for the exploration of various determinants and the formulation of reliable policy recommendations.
2. Another notable contribution of the study is to develop the DE index to analyze its effects on GG. The pertinent literature uses the variable single variables to measure the influence of DE. However, it has several aspects that cannot be covered by a single variable. Hence, to avoid the biased results, this study tends to develop a comprehensive DE Index that covers the six dimensions: Digital Economy Infrastructure (DEI), Digital Economy Innovation Environment (DEIE), National Digital Competitiveness (NDC), Digital Finance (DF), Digitalization Potential (DP), and Social Support (SOS). Based on 29 indicators, this index offers a more robust and reliable measure of digital economy.
3. Most of the previous studies rely on the linear method for the analysis that cannot handle the issue of nonlinearities; therefore, the results might be biased. To address nonlinearities and achieve robust policy recommendations, the present study uses the MMQR. Further, the study deploys the system GMM, to tackle the endogeneity. Also, this study performs a heterogeneous analysis to determine the likely heterogeneity. Additionally, the Nonparametric Panel Granger Causality (NPPGC) test is used to assert quantile-wise causality.

The remaining sections of the study are organized as follows: Section 2 provides an overview of the literature, Section 3 discusses the conceptual framework, Section 4 presents the methodology and data descriptions, Section 5 outlines empirical results, section 6 provides NPPGC analysis, and the final section concludes the study.

2. Literature Review

In recent decades, global economies have focused on green growth and DE. Environmentalists and researchers demonstrate that DE substantially contributes to increasing production efficiency, declining transportation and transaction costs, and reducing waste, significantly promoting green growth. Hence, the literature is divided into two sections: the first section elaborates on the connection between green growth and DE, and the second section highlights the connection between green growth and other control variables.

2.1 Green Growth and Digital Economy

The past bodies of literature can be classified the GG into three main segments based on their economic, social, and environmental perspectives towards the goals. Further, the primary part of the literature examines the connection between the DE and GG. The latest growth theory admits that the DE is essential for sustainable output growth. It enhances financial inclusion, innovations, and strengthens sustainable output growth (Li et al., 2025; Yao et al., 2023; Chapuzet, 2022; Liu et al., 2024). Another way it does this is by driving entrepreneurship (Xin et al., 2023) and raising globalization (Mayer et al., 2023). Nonetheless, Albiman and Sulong (2018) explain that DE without any form of economic transformation may disadvantage an economy.

Digital economies have several impacts on social development. Besides, the DE could foster GG because its widespread nature makes education cheaper at all levels. Further, it can create more opportunities for medical services. It helps reduce marginal costs and stimulate the productivity level. For example, Asongu et al. (2019) find that deepening ICTs plays a considerable role in improving education via poverty reduction policies that aim to reduce income inequality, among others. Also, Aloini, et al. (2023) suggested that digital technologies can boost health systems decentralization by breaking down geographical barriers and bringing healthcare providers closer to patients. Additionally, sustainable development could be achieved through a DE. Besides, with environmental protection, economies could achieve a GG level. Nevertheless, whether the DE has positive or adverse effects on sustainable development is still being determined. On the one hand, online trading and payment recommended by the platform model underpinning digital economies can reduce enterprises' travel and transaction costs and result in enhance the sustainable output (Yi et al., 2022; Chishti et al., 2022). Similarly, innovative energy systems development, along with intelligent industries and cities underpinned by the DE could save energy and decline environmental pollution (Chang et al., 2025; Avom et al., 2020). However, energy consumption by ICTs serving digital economies needs to be considered since this might lead to increased carbon dioxide emissions (Avom et al., 2020). Again, the inclusion of financial services brought about by the DE has led to investment and consumption activities that have further contributed towards increased levels of atmospheric pollution through the release of greenhouse gases into the air during fuel combustion processes (Qin et al., 2022). Consequently, positive, or negative effects may affect the environment, depending on the implementation strategies.

DE can be positively linked with GG for different reasons. One is that it can potentially enhance digital finance, globalization, entrepreneurship, stimulating economic growth. At the same time, increased allocation of digital resources and better use of ICT are known to create equal education and healthcare opportunities for all. Consequently, poverty reduction and income gaps among individuals will be reduced through the DE. Additionally, environmental conservation is another area where this kind of economy plays a positive role; it saves on energy consumption while cutting down carbon emissions and supporting cleaner technology production. *Thus, "based on the above debate that digital economy it seems that digital economy support to enhance the green growth."*

2.2 Green Growth and Other Variables

Recent literature considers these variables as a determinant of green growth. The government significantly enhances sustainable economic growth through investment in clean energy projects, sustainable infrastructure, and efficient resource allocation to foster innovation, generate green employment, and protect the environment. This literature review examines empirical studies on the effects of general government expenditures (GGE), trade openness (TRDOP), urbanization (URBN), and ecological taxes (EXT) on sustainable output growth. However, a number of previous studies, for instance, Bayraktar et al. (2015), Lamartina & Zaghini (2011), and Alexiou (2009), demonstrate that an increase in the level of GGE contributes to economic growth across the various regions of the GE. Also, for TRDOP, particularly in the emerging countries that enhance the output growth (Chishti et al., 2021; Chishti et al., 2020). Further, TRDOP enables less developed economies to import DT and helps upgrade the industry, leading to improved environmental quality (Jayanthakumaran et al., 2012; Antweiler et al., 2001; Boulatoff & Jenkins, 2010). However, past studies suggest that URBN plays a significant role in raising output growth levels while worsening environmental quality (Henderson, 2003; Sufyanullah et al., 2022; Fang et al., 2022; Liu & Bae, 2018). Thus, environmental protection taxes effectively reduce environmental degradation and pollution, as shown by studies in various regions, and result in stimulating sustainable output (Borozan, 2021; He et al., 2020).

3. Conceptual Framework

GG has been considered an essential strategy in recent decades; policymakers and government agencies globally seek to address the challenges of environmental consequences, ecological change, and sustainable output growth. Another study of UNEP (2012) indicates that green growth is a path toward output growth that is environmentally sustainable and socially inclusive. Hence, the conventional growth model achieves growth at the expense of environmental damage. Thus, environmentalists and researchers find the solution to adopt green growth because it creates the balance between environmental pollution and economic prosperity. Additionally, recent studies, (United Nations, 2024; Dinda, 2014; UNEP, 2012) highlight the importance of green growth and emphasize its role to achieve the sustainable development goals. In this way, the present study indicates that digital economy is considered as the 3rd biggest economy after the agriculture economy. The digital economy has the potential to attain sustainable output.

The digital economy (DE) has emerged as a pivotal force in global economic landscapes. The report of the United States (US) Bureau of Economic Analysis shows that the DE contributed 5.9% of GDP in 1997 and increased to 10.5% in 2021. This figure shows a significant increase in the DT in the US economy. On the other hand, the Global Digital Economy Report (2025) highlights that the DE has contributed to the United States (US) Bureau of Economic Analysis, demonstrating that it accounted for 5.9% of GDP in 1997 and increased to 15% of global GDP in 2024. This figure indicates that the DE has been growing sharply worldwide. The study by Maksimovic (2017) argues that DT is a vital catalyst for promoting innovation, stimulating effective resource utilization, and raising the level of GG (Ren et al., 2023; Gomes et al., 2022; Zhao & Qian, 2024). Further, it enhances online business activities, expands the market, and supports e-banking. A number of GE have emphasized the transformation of DT and invested heavily in digital infrastructure. Figure 1 presents the conceptual framework of the study.

Moreover, the DE promotes education facilities and medical services while reducing costs. It could lessen the burden on individuals (Chen et al., 2022). This is evidenced by Asongu et al. (2021), documenting the role digital economy strengthening performances in widening access to schooling among poor societies using pro-poor policies that control income inequality. Another study by Asongue et al. (2018) demonstrates that the DE may decrease travel and transaction costs through digital finance because people make transactions at home. Equally significant that digital technologies might be used to fight extreme poverty experienced across the world. E-commerce, a digital platform for entrepreneurship, could also be used by poor people from disadvantaged districts to improve human capacity for families with minimal resources through online knowledge transfer; henceforth, it narrows down wealth disparity because of internet industrialization Goralski and Tan (2022).

Thus, developing this model to investigate the link between GG and the DE is rational:

$$GG_t = f(DE_t) \quad (1)$$

Here

Government expenditure (GGE) significantly promotes GG by investing in digital infrastructure, green infrastructure, renewable energy projects, and sustainable urban planning (Zhang et al., 2021). Governments also allocate budgets for research and development in environmentally sustainable products, waste management, recycling, and eco-friendly materials, fostering sustainable growth (Kurniawan et al., 2022). These expenditures drive environmental innovations, benefiting both the environment and the economy (Sadiq et al., 2022). Thus, government spending on digital infrastructure, R&D, waste management, and ecosystem restoration is crucial for promoting GG and mitigating carbon emissions. So, government expenditures and the DE are crucial in promoting GG. Based on the above discussion, the model with GGE can be written as:

$$GG_t = f(DE_t, GGE_t) \quad (2)$$

As TRDOP plays a key role in the exchange of goods and services, it expands the market size. Further, changes in the patterns of production and consumption for individuals, driven by the transformation of DT from developed to developing economies, lead to a significant stimulation of the GG. Further, through trade, emerging economies benefit from installing modern machinery and updating production patterns, which stimulate efficiency and enhance the level of GG (Karakosta et al., 2010). So, the equation (2) can be modified as:

$$GG_t = f(DE_t, GGE_t, TRDOP_t) \quad (3)$$

However, in recent decades, GE has faced a significant issue with URBN. It adds many economic challenges, including shelter, food insecurity, traffic, access to clean water, sanitation, and jobs. Thus, the URBN is considered the vital determinant of GG (Ma et al., 2023; Ying et al., 2022). On the contrary, it plays a key role in boosting GE output. Government authorities and policymakers should take significant measures to address the adverse effects of URBN (Rashed, 2023). For this purpose, the government authorities should emphasize urban planning, eco-friendly technologies, and green infrastructure. Thus, equation (3), by incorporating URBN, can be written as:

$$GG_t = f(DE_t, GGE_t, TRDOP_t, URBN_t) \quad (4)$$

The GE faces significant environmental issues, especially in developing economies, due to weak institutions and a lack of enforcement to implement environmental taxes. These taxes play a key role in stimulating environmental performance (Fan et al., 2019). Further, EXT is the engine for promoting clean and green innovations that significantly reduce the burden on fossil fuels and encourage the use of alternative clean energy sources, which are key solutions to reduce CEs and improve environmental quality (Mpofu, 2022). Hence, equation (4) can be extended as

$$GG_t = f(DE_t, GGE_t, TRDOP_t, URBN_t, EXT_t) \quad (5)$$

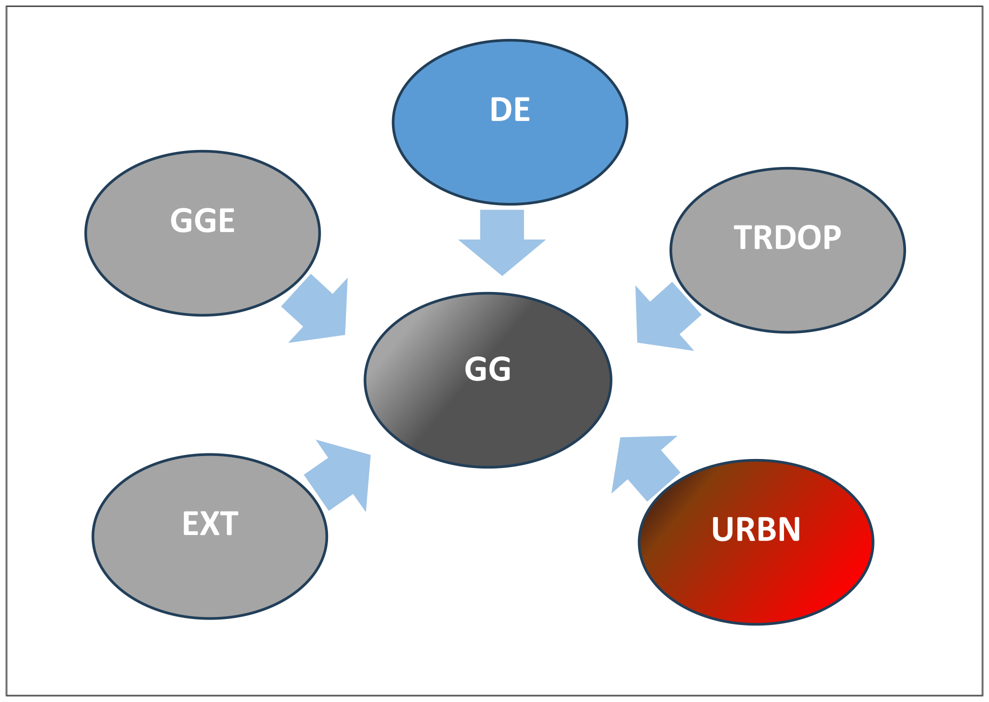

Fig. 1. Conceptual Framework

4. Methodology

4.1 Econometric Techniques

The study used various preliminary tests to assess the data and relevant econometric techniques. Due to globalization, economies are integrated, leading to cross-sectional dependencies. The study employs Pesaran et al. (2004) to inspect cross-sectional dependence and panel unit root tests (CIPS and CADF) to affirm data stationarity. Further, the present study uses Westerlund's (2007) cointegration to assess the long-run relationships between variables.

For short- and long-run coefficient values, the study employed MMQR, developed by Machado and Silva (2019), and system GMM techniques (Firpo et al., 2022; Arellano & Bover, 1995). These methods handle cross-sectional dependencies, endogeneity, and heterogeneity in panel time series. Compared to traditional methods, this approach addresses non-linearity, such as NARDL, and corrects location-dependent differences (An et al., 2021; Elbatanony et al., 2021). In addition, the MMQR estimates have the ability to capture the "conditional heterogeneous covariance effects" that affect the regressand of the whole data distributional effect (Koenker (2004; Canay, 2011) . The MMQR method is suitable for heterogeneity and non-linear combinations, handling endogeneity and heterogeneity without skewed estimates across structural quantiles (Razzaq et al., 202; Ahmad and Kalim, 2024). In the context of a space-scale model, the distribution of a given certain quantiles Qτ(τ| X) may be expressed as follows.

$$Y_{it}=a_i+(X^{`}_{it}\beta+(ʑ_i+Z^{`}_{it}£)U_{it} \quad (6)$$

Here in equation 6, it represents the probability is P +{$X^{`}_{it}$β + ($ʑ_i$ +$Z^{`}_{it}$£} >0 =1, $(a, \beta^{`}, ʑ, £^{`})^{`}$ U_{it} are parameters that need to be estimated and $(a_i, ʑ_i)$, we consider the individual fixed effect for each individual i in the range 1,…,n. Let Z be a k-dimensional vector and designate it as the component of X that is differentiable and transformed by the specified element.

$$Z_i = Z_i(X), 1,.., k \quad (7)$$

In addition to being invariant over time (t), In the context of the Machado and Silva moment, we consider a scenario where Xit possesses a distribution that is identical and independent for any fixed individual i. The instant conditions are met when Uit has an identical and independent distribution across individuals (i) and over time (t) while remaining orthogonal to Xit . Given equation (1), the following is the result that can be expected:

$$Q_t\left({}^{t}/_{X_{it}}\right) = (a_i + ꝛ_i q\,(t)) + X\grave{}_{it}\beta + Z\grave{}_{it}q \quad (8)$$

In this context, we have a vector of independent variables denoted as X_{it} . The expression in equation 8 $Q_t\left({}^{t}/_{X_{it}}\right)$ that specifies the conditional supply of the dependent variable $Y_{i,t}$, which is determined by the distribution of the explanatory variables X_{it}. Additionally, we introduce a scalar coefficient $a_i = a_i + ꝛ_i$q (t), where ϵi represents the fixed effect for individual identification (i). Unlike ordinary least squares (OLS) fixed effects, the individual effect does not exhibit intercept volatility. These parameters remain unaffected by the passage of time, and their heterogeneous effects can vary across different quantiles of the conditional distribution of the dependent variable.

Furthermore, in the optimization problem, q(t) represents the t-th sample quantile, derived by solving the following issue.

$$min_q = \sum_i \sum_t p_t\,(R_{it} - (ꝛ_i + Z\grave{}_{it}£)q) \quad (9)$$

Thus, the function in the proceeding function can be examined as:

$$\text{“}\rho\tau\,(A) = (t - 1)AI\{A \leq 0\} + TAI\{A > 0\}\text{”}. \quad (10)$$

In order to check the reliability of the MMQR estimates, the study used a two-step GMM estimation method. It was developed by Arellano and Bover (1995) and Blundell and Bond (1998). This technique is preferable to the GMM difference because it yields unreliable results when the dependent variable is a random walk. On the other hand, the two-step GMM system is the most efficient econometric method for handling large panel data sets. It can effectively address endogeneity, data outliers, and unobserved heterogeneity. Omitted attributes based on the instrumental variable incorporated twice (Roodman, 2009). It performs instrumental-variable estimation at the initial state and, in the second state, estimates the model's parameters.

In addition, the system GMM has been based on the two mathematical equations. The number one is original, and the 2nd is a transformation equation. This technique is more powerful than the one-type GMM. It reduces unnecessary data loss, addresses author correlation and heteroscedasticity, and provides reliable outcomes (Sheraz et al., 2022; Appiah et al., 2023). However, to check the validity of the outcome that obtained from the two step system GMM the post estimation tests are required to conduct such as Hansen test which is used to assess the validity of the instruments, and the 2nd is Arellano-Bond (ARBND) test to investigate the autocorrelation issues for the favorable outcome the null hypothesis for AR1 should be rejected, and for AR2 that needs to be accepted to tackle the autocorrelation issue (Roodman, 2009) . For econometric analysis, the present study uses Stata-17 software.

4.2 Non-Parametric Panel Ganger Causality Test (NPPGC)

For robustness examination, the present study used the NPPGC technique. It is recently developed by Dong et al. (2021). However, in the past literature, many Granger Causality (GC) techniques are available to inspect the causality direction among the considered variables. Hence, these techniques cannot tackle the panel data series' outliers, CSD, and heterogeneity. On the other hand, most researchers rely on D. Hurlin's (2012) GC test, which did not capture the CSD or asymmetric causality. However, NPPGC is an advanced econometric technique that is a hybrid and based on Balcilar et al. (2017), it would find the asymmetric causal connection between the variables. For example, the marginal density function between the two attributes can be expressed as:

$$Q_t\left({}^{Y_{it}}/_{I_{it}}\right) = a_i + \sum_{k=1}^{q} £^k\,(t)Y_{i.t-k} + \sum_{k=1}^{q} \beta^k\,(t)X_{i.t-k} + \mathcal{E}_{i,t\,(t)} \quad (11)$$

The term "a_i" is used to denote the fixed individual effects in the equation presented above. However, equation (11) is unable to account for the individual heterogeneity that has not been seen. In order to address this matter, Dong et al. (2021) developed the NPPGC by following Canay et al. (2021) and following a technique that consisted of two steps. First, a conventional panel model with fixed effects is implemented, which includes the following:

$$Y_{it} = a_i + \sum_{k=1}^{q} £^k\,(t)Y_{i.t-k} + \sum_{k=1}^{q} \beta^k\,(t)X_{i.t-k} + \mathcal{E}_{i,t\,(t)} \quad (12)$$

After that, the equation 12 can be stated as follows, after the fixed effects have been subtracted to account for unobserved heterogeneity:

$$\widehat{Y}_{i,t=} Y_{it} + \hat{a}_i \quad (13)$$

This is followed by the computation of $Q_t\left({}^{Y_{it}}/_{I_{it}}\right)$ Dong et al. (2021), in accordance with the instructions provided by Jeong et al. (2012), while employing the nonparametric Kernal approach as follows:

$$\widehat{Q}_{i,t} = \widehat{Y}_{it}/I_{it} = \Upsilon\left(\widehat{F_{i,t}/I_{i,t}}\right)^{-1}\left(t/I_{it}\right) \quad (14)$$

The NPPGC in mean is computed using the equation which may be found above. Given the magnitude of GC between the series, it may be concluded that the null hypothesis of no GC is not supported. In addition, the NPPGC test can deal with heterogeneity and cross section dependence, avoid misspecification errors, capture the likely asymmetries in the series, and deal with outliers (Dong et al., 2021). All these things are necessary in order to provide a robust result.

4.3 Data Source

The study aims to inspect the link between DE and GG. Due to data availability (see the country classification list in the appendices), the study selected a sample of 104 economies around the globe for the period 2000-2022. The global economies are classified into specific groups, i.e., high, upper-middle, lower-middle, and low-income, based on the World Bank (2024) income classification. Hence, the subsequent sections elaborate on constructing an index of the DE and GG.

4.3.1 Dependent Variable

This section details the construction of the Green Growth Index, which includes three primary dimensions: SOSB, ES, and GEOP. In addition, the current index is more comprehensive than the Global Green Growth Institute (GGGI) index (2020). Besides, the Global Green Growth Institute's index highlights the benchmark structure for the global economies. The GGG index provides cross-country comparisons over a short period of time and is based on policy orientation rather than econometric analysis. Moreover, several considered attributes have been adjusted or replaced to enhance cross-sectional stability. One of the most common issues is that the GGGI details or procedures used to measure the index are not publicly available. However, the present study follows the index of Ofori et al. (2023) and adds more dimensions for instance in the SOSB adds third category for istance, social protection and adds 3rd sub dimesion, i.e, green economic opportunities based on the prior research and the direction of GGGI (2020). Moreover, the study by Ofori et al. (2023 constructs an index based on 24 indicators across the two sub-dimensions of GG, i.e., SOSB and environmental sustainability.

The sub-dimension of green growth SOSB includes the social context and economic context. To capture the balance, SOSB social protection is the key component that improves the equity and well-being of society, which was missing from the previous index. To address this limitation, this study adds a social protection subcategory to capture the full impact of SOSB (Brock & Taylor, 2010). The social context includes sanitation, population density, potable water, transport infrastructure, life expectancy, and infant mortality. In addition, hygienic sanitation and access to clean water play a key role in reducing the burden of various diseases (Ofori et al., 2022; Asian Development Bank, 2013). On the other hand, rising population levels lead to a worsening quality of life and pose significant challenges, such as people being unable to meet basic needs like housing, clothing, jobs, and other social services. Thus, social context is a more important determinant of green growth. Moreover, the economic context is also an essential determinant of GG. It consists of income inequality, unemployment, changes in wealth, human capital, and income growth. It helps reduce the income gap across income groups and promote sustainable output growth (Ofori et al., 2022; Solow, 1956; Brock & Taylor, 2010). Lastly, social protection plays a key role in unexpected emergencies and economic uncertainty, helping them meet basic needs in the face of economic shocks (Acosta et al., 2020).

Table 1: ***Variables for Green Growth Index (GG)***

Variable	Symbol	Variable description	Data source
A. ***Socioeconomic sustainability*** **(i) Social context**			
Sanitation	*sanit*	"Percentage of the total population having access to better sanitation"	GGKP Data
Population density	*pop*	"Population density refers to the number of inhabitants per square km."	OECD Stat.
Potable water	*Powat*	"Percentage of the total population with access to upgraded drinking water sources"	GGKP Data
Infant mortality	*infmort*	"Infant mortality rate (per 1000 live births)"	WDI Data
Life expectancy	*Lifexp*	"Mean lifespan from birth, encompassing all individuals (in years)"	OECD Stat.

Transport infrastructure	*Trans*	“Composite index measuring the quality and efficiency of road, aviation, shipping and railroad transport infrastructure”	WDI
(ii) Economic context			
Changes in wealth	*Cwea*	“Per capita changes in wealth (measured in US$)	GGKP Data
Income growth	*Incgro*	Gross Domestic Product per capita, Purchasing Power Parity (in constant 2017 international dollars)”	GGKP Data
Income inequality	*Ineq*	“Gini index (0 = Lowest; 1 = Highest)”	GGKP Data
Human capital index	*Hci*	“The human capital index is calculated by considering the years of study and the economic benefits of education”	PWT
Unemployment	*unemp*	“Total unemployment as a percentage of the whole workforce)”	GGKP Data
(iii) Social Protection			
Pensionable age	*pa*	“Percentage of the population who have reached the age at which they are eligible to receive a pension and are now receiving one.”	UN
health coverage	*hc*	“Index of universal health coverage”	UN
Population living in slums	*pls*	“Urban slum population proportion”	UN
B. Environmental sustainability **(i) Natural capital**			
Agricultural land	*Agric*	“Percentage of land area dedicated to agriculture”	GGKP Data
Forest cover	*Forest*	“Percentage of land area covered by forests”	OECD Stat.
Temperature changes	*Temp*	“Annual surface temperature anomaly relative to the average temperature between 1951 and 1980.”	OECD Stat.
(ii) Environmental quality of life			
Exposure to ambient PM.2.5	*Amb*	“Population mean exposure to PM2.5”	OECD
Ambient PM.2.5 Mortalities	*ambmort*	“Death resulting from the inhalation of outdoor air pollutants Particulate Matter 2.5 (PM2.5)”	OECD
Ambient PM.2.5 welfare cost	*ambcost*	“Costs associated with early deaths caused by exposure to ambient PM2.5, measured in terms of GDP”	OECD
(ii) Environmental & resource productivity			
Methane emission	*Metha*	“The value represents the methane emissions from agricultural activities, measured in thousand metric tons of CO2 equivalent.”	GGKP Data
Natural resources rent	*Natres*	“Percentage of GDP derived from rents generated by natural resources”	GGKP Data
Renewable energy	*renener*	“Percentage of total final energy consumption derived from renewable sources”	WDI Data
Carbon intensity	*Carint*	“CO2 intensity level, primary energy”	WDI Data
Fossil fuel consumption	*fosiful*	“Percentage of total energy consumption derived from fossil fuels”	OECD Statistics
(iv) Economic opportunities & policy response			
Clean fuel usage	*cleanfuel*	“Percentage of the population with access to clean fuels and technologies for cooking”	WDI Data
Environmentally friendly technologies	*envtech*	“Production of environment-related technologies, % all”	OECD Statistics
C. Green economic opportunities			
Green investment	gi	“Adjusted net savings, which takes into account the economic impact of emission damage as a percentage of Gross National Income (%GNI)”	WDI

Green trade	gr	"Percentage of environmental goods' share in total exports	UN
Green employment	ge	Proportion of environmentally friendly jobs in the whole manufacturing workforce"	OECD
Green innovation	gin	"The proportion of patent applications in the field of environmental technology relative to the overall number of people employed"	WIPO

Note: WIPO is World Intellectual Property Organization; OECD is Organization for Economic Cooperation and Development; UN is United Nations; GGKP is Green Growth Knowledge Program; WDI is World Development Indicators; PWT is Penn World Tables.

Further, the sub dimension environmental sustainability of GG is included in the study to complete the agenda of international sustainability agreements, for instance, the Paris Agreement, Rio+20, and the Brundtland Commission; all of which emphasize sustainable output growth, social equity, and environmental protection. These agreements have four central pillars: enhancing environmental quality of life; preserving natural resources for future generations; increasing environmental resource productivity by focusing on the efficient utilization of natural resources; and achieving carbon neutrality (World Bank, 2017). Lastly, it emphasizes the economic opportunities and the policy response to implement strategic environmental policies to drive GG levels (Lamichhane et al., 2021).

Moreover, the present study incorporates the 3rd sub-dimension of green growth, namely GEOP, a comprehensive pillar based on green investment, green employment, green trade, and green innovations, which are directly linked to Sustainable Development Goal 12, which promotes the production and consumption of clean technologies. Thus, previous studies were unable to incorporate this dimension, which is an integral part of measuring GG (GGGI, 2020). In previous studies, principal component analysis was used to construct the GG index. By the following studies (Ofori & Asongu, 2021; Lamichhane et al., 2021; Jolliffe, 2010; O'Rourke & Hatcher, 2013), this study has used PCA and constructed the index of GG, which is based on three dimensions: socioeconomic sustainability, environmental sustainability (ES), and green economic opportunities, and consists of 34 indicators for instance as shown in Figure 2, and details of the attributes are reported in Table 1.

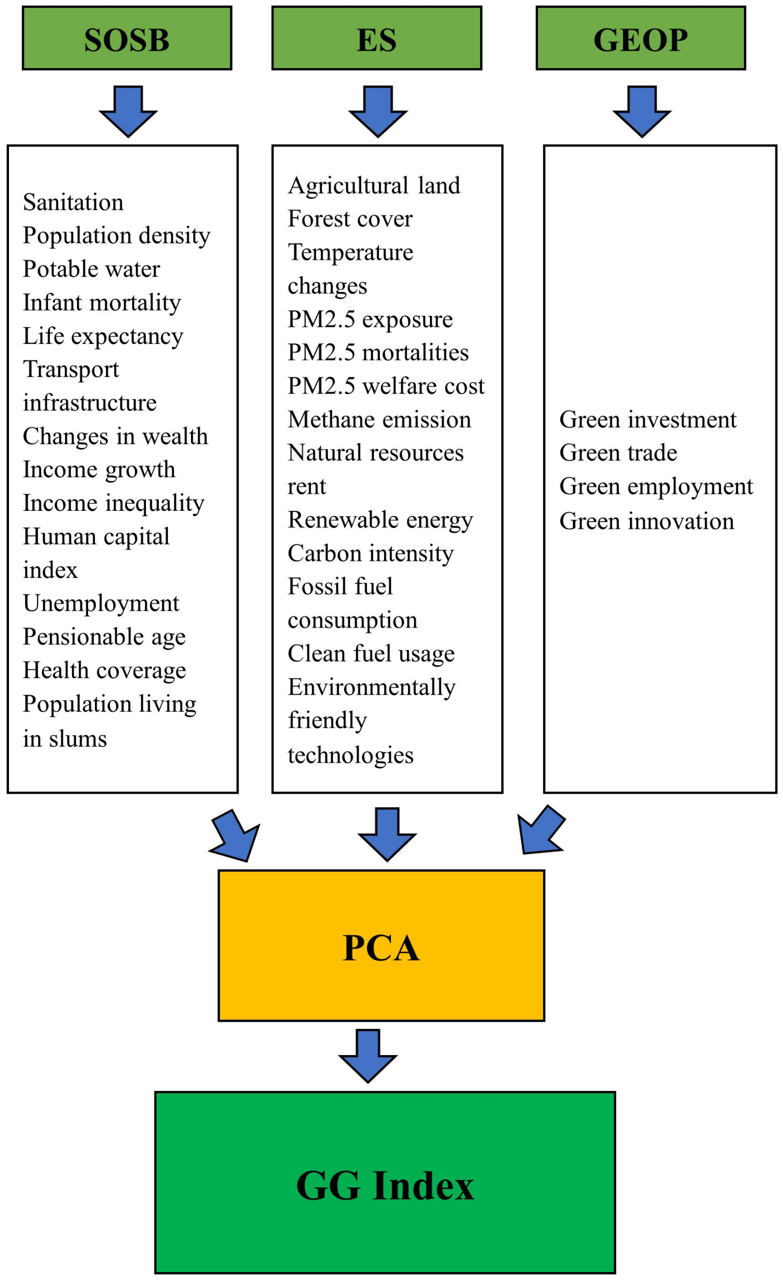

Fig.2: Shows the construction of GG index

4.3.2 Core Independent Variable

This section highlights the construction of DE index. The DE is mainly reflected in some information and communication technology research. However, they do not have a clear understanding of what precisely the DE is about. Therefore, the indicator system they construct scientifically and rationally also needs this understanding, leading to several shortcomings and one-sidedness of their research results. Similarly, there are no standardized official methodologies for calculating the level of development of the DE. Further, this index is more comprehensive than the Digital Economy and Society Index (DESI) (2022). Hence, the DESI is policy specific and based on the specific to regions, such as the EU. In addition, the study by Dong et al. (2022) developed the DE index based on a panel of 60 economies and a limited set of dimensions, DEI, DEIE, and NDC. Nevertheless, the DF, DP and SS are essential parts of DE that are missing in prior studies. As such, we chose 29 indicators that comprehensively measure the developmental stage of a national DE in terms of factors such as DE infrastructure, DF systems and services, and SS systems that aid in healthcare provision, among others. Therefore, it is based on these sets of indicators that were developed by previous studies (Teng & Qiao, 2023; Zhang & Chen, 2019) and those published by international bodies like the International Telecommunication Union and World Economic Forum as well as data availability and accurate description characters of the DE that allows us/when we can choose 29 indices for this purpose which covers all aspects like; physical infrastructures, financial systems for electronic money and online banking transactions including e-commerce platforms with cash payment facilities embedded in them towards health care provision as shown figure 3 the construction of DE index. Table 2 displays the details and description of each indicator and each dimension of the digital economy.

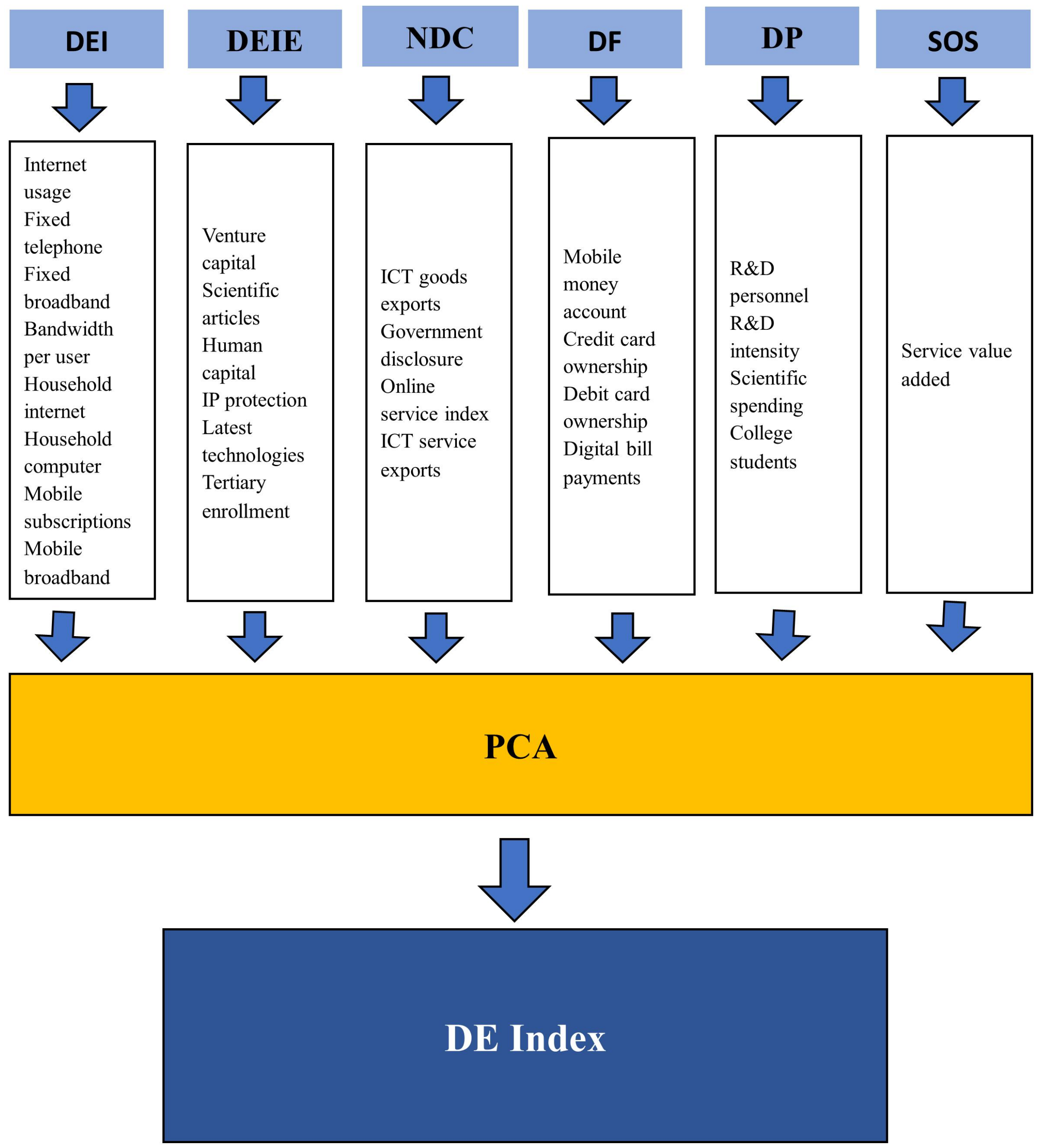

Fig.3 Construction of the digital economy index

4.3.3 Control Variables

The current study incorporates four control variables in order to avoid omitting variable biasness, namely general government expenditures To avoid omitting variable(GGE), which is measured by all the current government spending; trade openness (TRDOP) is measured by the sum of exports and imports of goods and services by the percentage of GDP; urban population (URBN), is the percental of the total population living in urban areas; and last variable is ecological taxes (EXT), tax revenue percentage of GDP. The data on general government expenses, trade openness, and urban population is extracted from the World Indicators database, while economic tax data is extracted from OECD statistics.

Table 2: Variables for the construction of Index for Digital Economy

	Symbols	Secondary indicators	Data Source
Primary index		"Individuals using the internet (% of population)"	ITU
Digital economy infrastructure	DI	"Fixed-telephone subscriptions (per 100 inhabitants)"	ITU
		"Fixed broadband subscriptions (per 100 people)"	ITU
		"International bandwidth per internet user (bit/s)"	ITU

		"% of households with internet"	ITU
		"% of households with computer"	ITU
		"Mobile cellular subscriptions (per 100 people)"	ITU
		"Active mobile-broadband subscriptions (per 100 inhabitants)"	ITU
		"Venture capital availability"	WEF
		"Scientific and technical journal articles"	WDI
Digital economy innovation environment	DEIE	"Human capital index"	EGOVKB
		"Intellectual property protection"	WEF
		"Availability of latest technologies"	WEF
		"School enrollment, tertiary (% gross)"	WDI
		"ICT goods exports (% of total goods exports)"	WDI
National digital competitiveness	NDC	"Government information disclosure and network participation"	EGOVKB
		"Government online service index"	EGOVKB
		"ICT service exports (% of service exports)"	WDI
Digital Finance	DF	"Mobile money account (% age 15+)"	WDI
		"Owns a credit card (% age 15+)"	WDI
		"Owns a debit card (% age 15+)"	WDI
		"Used a mobile phone or the internet to pay bills (% age 15+)"	WDI
Digitalization potential	DP	"Regional research and development personnel"	OECD
		"R and D intensity"	WDI
		"Proportion of scientific spending in the financial budget"	OECD
		"Number of college students"	WDI
Social Support	SS	"Per capita value added of service industry"	WDI

Note: ITU is International Telecommunication Union; WEF is World Economic Forum; WDI is World Development Indicators; OECD is Organization for Economic Cooperation and Development; EGOVKB is United Nations E-Government knowledgebase

5. Results

In Table 3, descriptive statistical results reveal that the mean value of GG is -0.028, lower than all other variables. Conversely, TRDOP has a mean value of 85.308, surpassing all other variables. Table 4 presents the cross-sectional dependence test and heterogeneity results, indicating the presence of such effects in the considered variables. This study employs second-generation unit root tests, including the cross-sectionally augmented Dickey-Fuller test and the Cross-Sectionally Augmented IPS (CIPS) test by Pesaran (2007). CIPS results reports in table 5 show that GG and DE exhibit no unit root, while other variables become stationary after first differencing. Additionally, the CADF test yields similar outcomes, except for GG. Additionally, Table 6 elaborates on the Westerlund cointegration. The finding from the Westerlund cointegration confirms a long-term relationship among the selected global country variables.

Table 3: ***Descriptive Statistics***

	GG	DE	GGE	TRDOP	URBN	EXT
Mean	-0.028	-0.094	15.517	85.308	1.967	1.732
Median	0.907	-0.708	15.805	74.102	1.7307	1.940
Maximum	5.425	10.926	43.482	437.327	19.612	6.4000

Minimum	-8.714	-6.136	1.000	2.000	-14.025	-1.53
Jarque-Bera	293.564	162.286	297.127	9575.742	18005.80	28.317
Probability	0.000	0.000	0.000	0.000	0.000	0.000

Table 4: ***Cross-Section Dependence And Slope Heterogeneity Tests***

Panel A		
Variables	**T-Stats.**	
GG	63.06***	
DE	43.67***	
GGE	41.90***	
TRDOP	51.15***	
URBN	19.14***	
EXT	19.31***	
Panel B		
Slope Heterogeneity test		
	$\widetilde{\Delta}$	$\widetilde{\Delta}_{Adjusted}$
Model	33.19***	39.46***

Note: *** indicates the 1% significance level. Source: Authors' estimation.

Table 5: ***Second Generation Unit Root Tests***

	GG	**DE**	**GGE**	**TRDOP**	**URBN**	**EXT**
CIPS						
I (0)	-2.74***	-2.254***	-1.513	-1.128	-1.959	-0.970
I (1)			-3.681***	-3.513***	-3.789***	-2.663***
CADF						
I (0)	-1.793	-2.118***	-1.334	-0.839	-1.17	-1.630
I (1)	-2.541***		-3.84***	-1.905**	-1.944*	-2.064***

Note: *** & ** indicate the level of significance at 1% and 5%, respectively. Source: Authors' estimation.

Table 6: ***Westerlund (2007) Cointegration Test***

Statistic	**Gt**	**Ga**	**Pt**	**Pa**
Model	-7.033***	-8.622***	-30.722***	-11.702***

Note: *** indicates the 1% significance level. Source: Authors' estimation.

Table 7 presents the MMQR estimates for the lower, median, and upper quantiles. On the other hand, Table 8 provides the long-run coefficient values of the selected attributes. The findings from both econometric methods show a considerable effect of DE on the GG across global economies. The influence of the DE remains consistent in heterogeneous analysis. GGE, TRDOP, and EXT positively connect with GG in the lower, medium, and higher quantiles, while URBN shows a negative link, indicating urbanization worsens environmental quality. Green urbanization is necessary for environmental sustainability. The system GMM is a two-step technique to address endogeneity, and finding is consistent to MMQR. Additionally, the findings show that DE significantly stimulates sustainable growth in the long term, with TRDIP, GGE, and ecological taxes positively linked to GG, while URNN has a negative link. The system GMM results confirm the reliability of the findings. In addition, the present conducts various post-estimation tests, for instance, the Arellano-Bond statistics, AR1 and AR2, the Hansen and Sargan tests, and the outcomes are reported in Table 8. The AR1 test does not confirm the presence of first-order residual serial correlation, as indicated by the rejection of the null hypothesis. However, the findings for AR2 are minimally significant, and the outcome indicates a slight presence of second-order correlation; overall, the model is stable and reliable. For the validity of the instruments. The study employed the Hansen and Sargan tests; the probability values are 0.115 and 0.126, which are insignificant, resulting in accepting the null hypothesis. The outcome confirms the validity of the instruments.

Table 7: ***MMQR Estimates for the Global Economies***

	Lower quantiles		Median quantiles	Upper quantiles	
	0.10	0.25	0.50	0.75	0.90
DE	0.850***	0.786**	0.684***	0.622***	0.639***
GGE	-0.012**	-0.006***	0.002***	0.008***	0.012***
TRDOP	0.008***	0.008***	0.007***	0.007***	0.007***
URBN	-0.690**	-0.542**	-0.361***	-0.200**	-0.101**
EXT	0.071*	0.025**	0.031*	0.081**	0.111**S
No. of obs.	2266				

Note: ***, **, * signify the 1%, 5%, & 10% significance level, respectively. Source: Authors' estimation.

Table 8: ***System GMM Two Steps Estimate for Global Economies***

	Coefficient Value	Standard Error
L. GG	0.947***	0.003
DE	0.023***	0.002
GGE	0.091**	0.047
TRDOP	0.057***	0.018
URBN	-0.010***	0.003
EXT	0.079***	0.011
Constant	-0.037***	0.014
Observations	2226	
Wald test		524057.92
Number of Groups	104	
Number of instruments	9	
AR1	-7.93	
	(0.000)	
AR2	2.58	
	(0.010)	
Hansen	2.49	
	(0.115)	
Sargan test	0.94	
	(0.626_	

5.1 Heterogeneous Analysis

Tables 9, 10, 11, and 12 display the results on basis on income group levels of economies such as high, upper-high, lower-middle, and low-middle classes. The outcome from the MMQR indicates that DE reveals a positive effect on GG across all income groups. The outcomes are consisting with the global sample and as well as with the system GMM. However, the coefficient value of DE for low-middle- and low-income economies is higher than other income groups. The reason is that emerging economies sharply increase the use digital products and services, i.e., online banking, buying and selling of goods and services on intent, which reduces the travel and transaction cost. So, the GG is affected more by the DE than high-income group economies.

Further, the finding indicates that TRDOP and URBN exhibit a significant and positive effect on GG in lower, median and upper quantiles and across various income groups. In contrast, the findings indicate that URBN destroys environmental sustainability and worsens the GG level around all income groups. Thus, the findings indicate that GGE significantly reduces the GG level at the inrail quantile, median and upper quantile, showing a positive effect of GGE on GG around all income groups

Table 9: ***MMQR Estimates of High-Income Group Economies***

	Lower quantiles		**Median quantiles**	**Upper quantiles**	
	0.10	0.25	0.50	0.75	0.90
DE	0.261***	0.238***	0.207***	0.225***	0.231***
GGE	-0.022**	0.013***	0.033***	0.057***	0.067***
TRDOP	0.003***	0.003***	0.004***	0.006***	0.007***
URBN	-0.080***	-0.087***	-0.048***	-0.066***	-0.050***
EXT	0.386***	0.263***	0.324***	0.276***	0.288***
No of obs.	1011				

Note: ***, **, * signify the 1%, 5%, & 10% significance level, respectively. Source: Authors' estimation

Table 10. MMQR estimates of upper middle-income group economies

	Lower quantiles		**Median quantiles**	**Upper quantiles**	
	0.10	0.25	0.50	0.75	0.90
DE	0.636***	0.624***	0.436***	0.387***	0.371***
GGE	-0.065***	-0.038***	0.003***	0.072***	0.088***
TRDOP	0.014***	0.018***	0.014***	0.011***	0.009***
URBN	-0.088	-0.317	-0.176***	-0.293***	-0.241***
EXT	-0.060***	-0.341***	-0.065	0.025	0.130*
No. of obs.	595				

Note: ***, **, * signify the 1%, 5%, & 10% significance level, respectively. Source: Authors' estimation

Table 11: ***MMQR Estimates Of Low Middle-Income Group Economies***

	Lower quantiles		**Median quantiles**	**Upper quantiles**	
	0.10	0.25	0.50	0.75	0.90
DE	1.342***	1.327***	0.921***	0.730***	0.636***
GGE	-0.006	-0.017*	0.054***	0.147***	0.196***
TRDOP	0.007**	0.010***	0.009***	-0.002	-0.013***
URBN	-0.194***	-0.173***	-0.520***	-0.245***	-0.176***
EXT	0.060	0.199**	0.301*	0.265*	0.636***
No. of obs.	644				

Note: ***, **, * signify the 1%, 5%, & 10% significance level, respectively. Source: Authors' estimation

Table 12: ***MMQR Estimates of Low-Income Group Economies***

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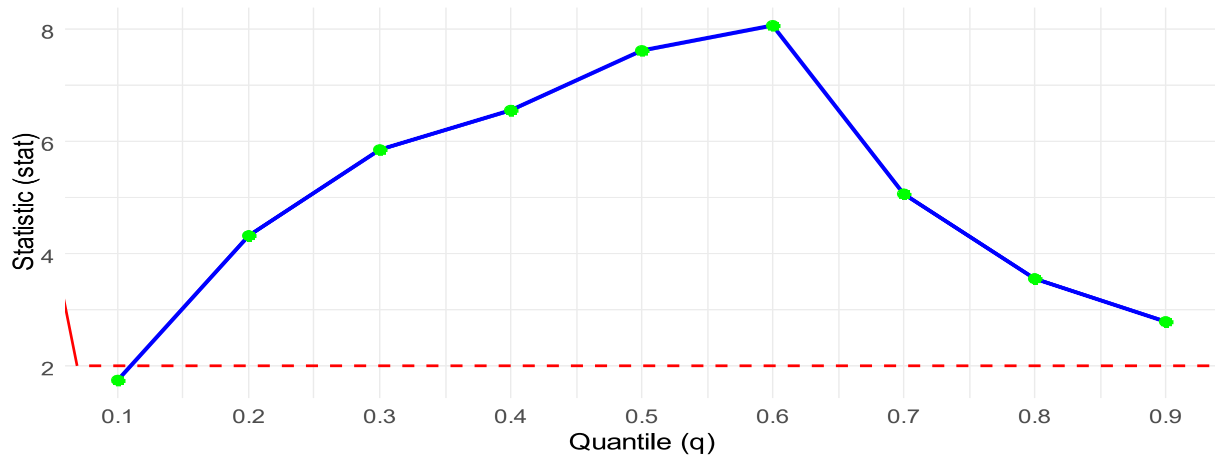
	Lower quantiles		Median quantiles	Upper quantiles	
	0.10	0.25	0.50	0.75	0.90
DE	1.450***	1.455***	1.485***	1.206***	1.168***
GGE	-0.012	-0.004	0.014	-0.020	-0.014
TRDOP	0.017***	0.012*	0.009	-0.004	-0.001
URBN	0.011	0.099	0.254**	0.323***	0.274***
EXT	-0.800***	-0.797*	-0.565***	-0.786***	0.760***
No. of obs.	184				

Note: ***, **, * signify the 1%, 5%, & 10% significance level, respectively. Source: Authors' estimation

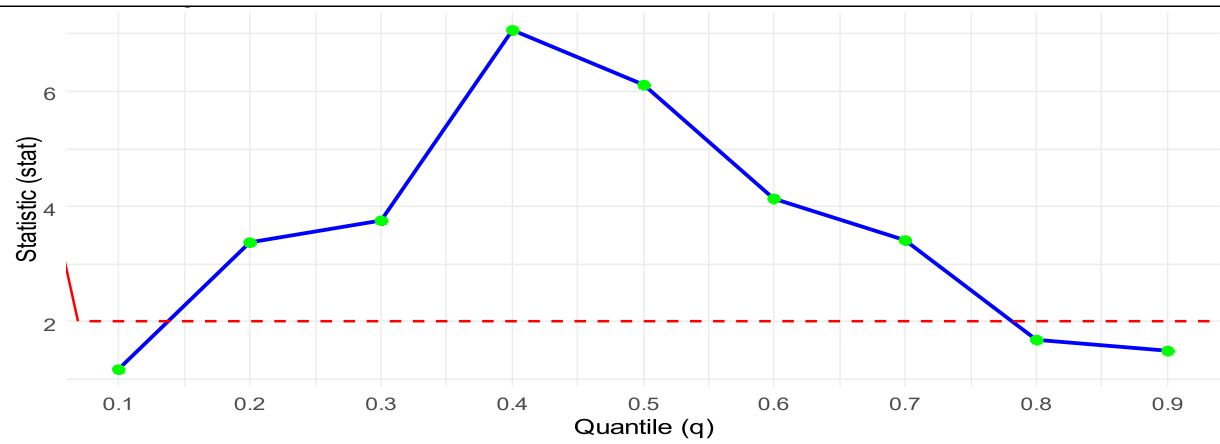
5.2 Non-Parametric Panel Ganger Causality Outcome

The present study incorporates the novel NPPGC test for the causal connection between the considered attributes. The blue line shows the estimated value. On the other hand, the red dotted line shows the test statistics value. If the estimated value is greater than the tested value, it confirms the presence of GC. The findings are portrayed in Fig. 4. The outcome depicts a causal connection between DE and GG in the short and long run. Hence, the quantile level of 0.1 to 0.03 shows a short run; on the contrary, 0.7 to 0.9 indicates a long run, while 04 to 0.6 indicates a median quantile. However, the outcome elaborates that DE shows a causal connection both in the short run and long. Further, the outcome shows that GGE revealed a GC in the short run, at the median level, and in the long run at 0.8 quantile level.

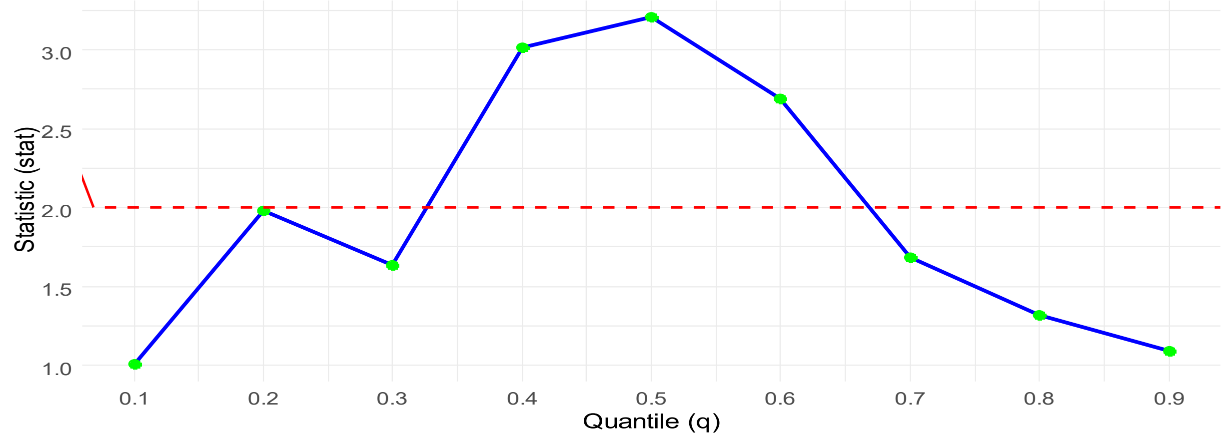
In contrast, the finding depicts that TRDOP implies a more significant cause at the median level. In comparison, the short and long run have an insignificant effect. Thus, the outcome depicts that the URBN shows a GC across all quantiles. The turnout for ecological tax indicates that in normal periods, EXT shows a GC with GGE.



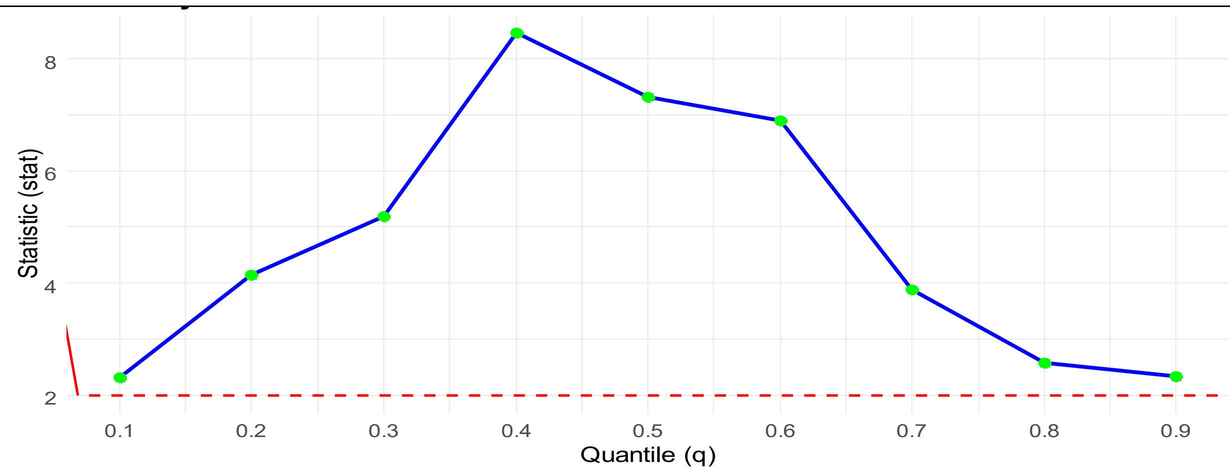
Causality from DE to GG



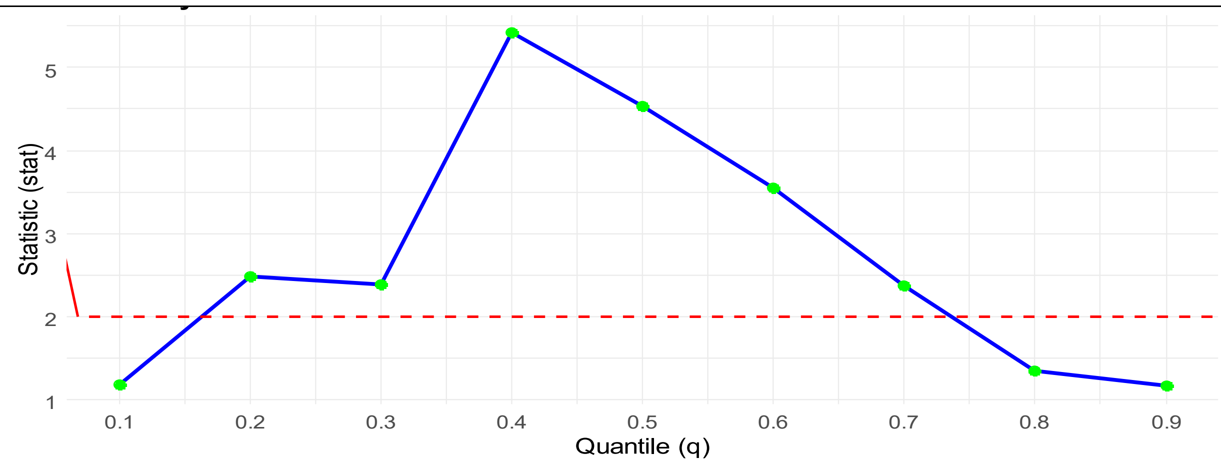
Causality from GGE to GG



Causality from TRDOP to GG



Causality from URBN to GG



Causality from EXT to GG

Fig. 4: NPGC Test`s Outcomes. Source Authors' Estimation

5.3: Discussion

The results indicate that the DE positively influences GG across short-, medium-, and long-run quantiles globally and regionally. The DE coefficient is higher than in other regions. Chapuzet (2022) suggests that the DE promotes digital finance, significantly stimulating sustainable growth. Another study by Asongue et al. (2018) shows that increases in the DT significantly reduce the burden on customers and businesses. It enables instant payments anytime, anywhere, reducing transaction and travel costs and lowering carbon emissions. Furthermore, Goralski and Tan (2022) argue that DE opens new markets, creates new businesses, and generates job opportunities, which play a key role in overcoming poverty, especially in the poor areas of the GE. Further, the outcomes align with Sudoh (2005) and Qian et al. (2020), who emphasized the importance of DE in addressing environmental challenges that are associated with GE. A further study by Martynenko and Vershinina (2018) DE reshapes the GE through innovations and automation processes, reducing waste through efficient resource utilization, thereby stimulating the level of GG.

The GGE outcome shows that a rise in public expenditures stimulates the GG across all quantile levels. In addition, the findings are similar across income groups in the rest of the low-income economies. On the other hand, developed countries allocate more budget to infrastructure development, especially in education, health, and waste management, and these economies spend about 46.3% of GDP (OECD, 2024). The results align with previous studies, for instance, Mikho et al. (2021), and Bernauer and Koubi (2013) argue that GGEs play a key role in promoting the GG by investing in DT, which leads to a reduction in CEs. Moreover, the study's findings align with Saqib et al. (2020), which highlight that the GGE stimulates sustainable output growth.

The results for TRDOP indicate a positive influence on GG, especially in developing economies. The findings are the same as those of Wei et al. (2024) and Cui et al. (2020). Surprisingly, the outcome for URBN significantly improves CEs, worsening environmental quality. Further, the URBN poses significant environmental challenges, for instance, transport issues, water and sanitation problems, overburdening the cities' housing and slums issues, job insecurity, and healthcare issues that adversely affect the well-being of the economies and reduce the level of GG (Fan et al., 2022; Kwilinski et al., 2023). The findings of the study align with a previous study by Sudoh (2022), which suggests that a rise in URBN levels considerably increases CEs and worsens ecological quality. On the other hand, the study's findings are the opposite, showing that intelligent management of URB plays a vital role in stimulating innovation and reducing income inequality through investment in clean and green technologies (Turok & McGranahan, 2019; Mohanty, 2022).

The EXT outcome shows a positive influence on GG at all quantitative levels and across all income groups. The results align with the past studies; for instance, Fan et al. (2019) highlight that the strategic environmental policies and carbon taxes lead to improved environmental quality. The study by Aydin and Esen (2018) argues that EXT encourages business units to promote innovation and upgrade machinery to benefit from it, thereby reducing CEs. In addition, the study by He et al. (2019) found that EXT significantly reduces CEs across OECD economies.

6. Conclusion and Policy Implications

The purpose of the study is to examine the relationships among DE, GGE, TRDOP, URBN, EXT, and GG. The empirical analysis has been conducted on a panel of 104 economies. The data spans the period 2000 to 2022. In addition, the sample size is large, and the study is based on a global panel. In recent years, many economies have become more integrated through trade and globalization, and data face issues of cross-sectional dependence and outliers. To tackle these issues, this study employed two advanced econometric methods, namely MMRQ estimates and system GG. Further, the current study divided economies into various income groups, for instance, low, lower middle, upper middle, and high income groups, to assess the impact of DE on GG in each income group. The empirical findings from the MMQR estimates demonstrate that an increase in the level of DE significantly influences the GG at the lower, median, and higher quantiles globally. In addition, the heterogeneous analysis indicates that the marginal effect of DE on GG is higher in lower- and middle-income economies than in high-income economies. Hence, to check the robustness of the results, the study used GMM. The GMM findings are similar to those of MMQR, indicating the results' reliability and validity. However, the outcome for the other attributes, such as TRDOP, GGE, and EXT, revealed a positive impact on GG. On the one hand, the findings for URBN indicate a negative influence on GG. The empirical results concluded that DE is a vital catalyst for stimulating GG around the GE. Further, the turnout suggests that the impact of DE is more substantial in the low-income group than in the high-income group. These findings reveal that emerging economies need to invest more in digital transformation to enhance the GG level as a priority.

For this purpose, the government bodies of emerging economies should invest in promoting the digital infrastructure to accelerate the pace of digital transformation. It promotes innovation, e-commerce, e-banking, and e-learning systems because these platforms help create new businesses and new job markets, significantly reducing unemployment levels, particularly in less developed economies. Further, the environmentalists, policymakers, and government authorities should prioritize digitalization efforts, emphasize the transfer of digital technologies from developed to less developed economies, establish smart innovation hubs, and set up training centers to raise public awareness of the latest information on digital skills. In addition, government authorities should redefine trade policies to improve economic conditions and facilitate the transformation of digital technologies, so that poor economies can also benefit from digitalization. Moreover, domestic economies should focus on stringent, strategic environmental policies and taxes to discourage conventional production techniques that worsen environmental quality, and to provide incentives for the promotion of innovative, efficient technologies that could help reduce CEs and improve ecological performance. Also, it is essential to design cities that have spaces covered with greens, efficient public transport systems, and sustainable infrastructures. Urban poverty eradication, along with informal settlement improvement, is needed for the sustainable improvement of living conditions.

The following are the limitations of this research that should be addressed in the future. First and foremost, this analysis mainly focuses on the fixed relationship between GG and the DE with no consideration of dynamic effects. In future research, these dynamics should be analyzed by incorporating lagged relationships and differentiating between immediate and long-term impacts of a change in GG level. Moreover, the study does not consider that policy dynamics could vary across regions and economic environments.Moreover, the analysis does not discuss how the DE affects varying sectors differently. Further studies would be necessary to investigate the sector-specific impacts of digitization on agriculture, manufacturing services, etc. Additionally, no attention is paid to marginalized people within the studied societies. Such groups could benefit from digitalization by bridging gaps, reducing inequality and fostering social and environmental justice. Hence, understanding these angles can give broader ideas on how the DE can contribute to inclusive, sustainable growth.

Data Availability Data and outcomes of the current study will be available on demand from the corresponding author.

Appendices

List of Countries

High-income	Upper-middle-income	Lower-middle-income	Low-income
Oman	Namibia	Zambia	Sierra Leone
Barbados	South Africa	Nigeria	Mozambique
New Zealand	Peru	Angola	Guinea
Kuwait	Belize	Cameroon	Madagascar
Saudi Arabia	Iraq	Pakistan	Niger
Bahrain	Ecuador	Myanmar	Mali
United Arab Emirates	Colombia	India	Ethiopia
Qatar	Brazil	Guatemala	Rwanda
Portugal	Lebanon	Nicaragua	Uganda
Greece	Azerbaijan	Honduras	Benin
Trinidad and Tobago	Panama	Paraguay	Lesotho
Spain	Uruguay	Indonesia	Kenya
Estonia	Jamaica	Mongolia	Zimbabwe
Cyprus	Costa Rica	Philippines	Senegal
Ireland	Mexico	Sri Lanka	Cambodia
France	Algeria	Morocco	Bangladesh
Australia	Argentina	Albania	Tajikistan
United States	Thailand	Tunisia	
Sweden	Mauritius	Jordan	
United Kingdom	Chile	Armenia	
Finland	Kazakhstan	Uzbekistan	
Italy	China	Ukraine	
Japan	Latvia		
Israel	Lithuania		
Malta	Malaysia		
Luxembourg	Romania		
Norway	Belarus		
Austria	Croatia		
Denmark	Poland		
Switzerland	Hungary		
Belgium			
Slovenia			
Netherlands			
Germany			
Singapore			

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