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SUSTAINABLE JOURNEY: THE IMPACT OF GREEN ECONOMIC GROWTH THROUGH THE MONTE CARLO ALGORITHM IN BAYESIAN INFERENCE

JORNADA SUSTENTÁVEL: O IMPACTO DO CRESCIMENTO ECONÔMICO VERDE ATRAVÉS DO ALGORITMO DE MONTE CARLO NA INFERÊNCIA BAYESIANA

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Abstract

The transition of the economy from "brown" to "green" places green economic growth as an indispensable instrument in this process. However, research examining the impact of green economic growth on sustainable development remains limited. This study seeks to address this gap by investigating the influence of green economic growth on sustainable development in 50 countries during the period from 2004 to 2021. Using the Bayesian regression approach, the results show that green economic growth has a positive effect on sustainable development (0.148), reflecting the importance of green economic growth in enhancing sustainable development across countries. These findings emphasize the need to further promote green economic growth as a key strategic direction, and to strengthen and improve policies that support the long term development of a green economy toward the goal of sustainable development.

Keywords: Green Economic Growth. Financial Development. Sustainable Development. Bayesian Regression.

Resumo

A transição da economia de "marrom" para "verde" coloca o crescimento econômico verde como um instrumento indispensável nesse processo. No entanto, a pesquisa que examina o impacto do crescimento econômico verde no desenvolvimento sustentável ainda é limitada. Este estudo busca preencher essa lacuna, investigando a influência do crescimento econômico verde no desenvolvimento sustentável em 50 países durante o período de 2004 a 2021. Utilizando a abordagem de regressão Bayesiana, os resultados mostram que o crescimento econômico verde tem um efeito positivo no desenvolvimento sustentável (0,148), refletindo a importância do crescimento econômico verde para o aprimoramento do desenvolvimento sustentável em diversos países. Essas descobertas enfatizam a necessidade de promover ainda mais o crescimento econômico verde como uma direção estratégica fundamental e de fortalecer e aprimorar as políticas que apoiam o desenvolvimento de longo prazo de uma economia verde rumo ao objetivo do desenvolvimento sustentável.

Palavras-chave: *Crescimento Econômico Verde. Desenvolvimento Financeiro. Desenvolvimento Sustentável. Regressão Bayesiana.*

1 INTRODUCTION

Environmental issues are becoming a global challenge and require appropriate tools and measures to address them without hindering economic growth (Kwilinski et al., 2023). In response to this situation, the European Commission adopted the Green Deal policy (European Commission, 2019), which provides a guiding framework for achieving a carbon-neutral economic growth pathway. At present, the global economy is undergoing a major transformation, and the shift in economic structure from “brown” to “green” requires countries to reshape their development process toward a greener direction. According to the Sustainable Development Goals (SDGs), economic growth must be accompanied by a transition toward carbon neutrality and a reduction in greenhouse gas emissions (Pan et al., 2019). In this context, green economic growth (GEG) aims to maximize resource efficiency and the effective use of production inputs such as labor, capital, energy, land, and education. At the same time, it promotes lowering greenhouse gas emissions and reducing negative impacts on the natural environment. GEG has become an important factor in promoting sustainable development and addressing issues related to social equity (Armutcu et al., 2024). In addition, GEG can generate significant economic, social, and environmental benefits (Lin & Zhou, 2022). It can be seen that GEG represents a model for sustainable economic development by emphasizing the alignment between economic growth, social harmony, and environmental improvement. Based on observed data, global sustainability levels have tended to increase over the years (SDGs, 2024), showing that countries worldwide are focusing more on sustainable development. As nations seek pathways to cope with climate change, identifying the actual role of GEG in sustainable development becomes highly important. At the same time, GEG opens opportunities for a full economic restructuring through green investment, the circular economy, and clean technology transition (Dong et al., 2024). This study aims to address the essential question of how GEG affects sustainable development across countries. The importance of this topic stems from the urgent need to move toward sustainability and the potential of GEG to reshape the global economic landscape. Therefore, the study concentrates on two main questions: (1) How does GEG influence sustainable development? and (2) Which GEG-related policies should countries prioritize in the current era of sustainable development? In addition, the study expects to provide meaningful empirical evidence to support policy making and development strategies during this challenging phase of green transition.

2 THEORETICAL AND LITERATURE REVIEW

2.1 Theoretical foundation

Theoretical frameworks for the impact of Green Economic Growth (GEGon sustainable development can be approached through the following theories:

The Porter Hypothesis, introduced and developed by Porter and Linde (1995, 1996) emphasizes that stringent environmental regulations stimulate innovation and enhance long-term socio-economic efficiency. In this context, GEG, achieved through the transition to a green economy via policies promoting resource efficiency, emission reduction, and enhanced economic stability, aligns with this hypothesis. Within this framework, stringent environmental regulations will promote green innovation, reduce costs and actively contribute to mitigating environmental degradation; Consequently, this plays a vital role in social stabilization and advancing sustainable development.

Public Disclosure Theory, pioneered by Diamond & Verrecchia (1991) and grounded in Asymmetric Information Theory (George, 1970), explains how transparent information disclosure by governments reduces information asymmetry and builds trust in the economy. Green Economic Growth (GEG), by providing reliable information on economic, social, and environmental performance, mitigates information asymmetry between countries and international investors, thereby lowering the national cost of capital. This process also fosters a transparent economic environment, reducing opportunities for corruption and advancing sustainability. Historically, attracting international capital was often short-term and hindered by a lack of credible "green" economic or environmental data, or by disclosures that were merely performative. GEG opens avenues for global integration, attracting long-term foreign investment and facilitating the transfer of clean technology, which contributes directly to sustainable development.

Signaling Theory (Spence, 1973) posits that information asymmetry is common among economic agents. The better-informed party can send credible signals to reduce this asymmetry and influence the expectations of the market, investors, and society.

Within this framework, Green Economic Growth (GEG) acts as a powerful signal. By transforming the economic structure away from the "brown economy" through enhanced resource efficiency, reduced environmental harm, and the promotion of green technological innovation, GEG sends a strong positive signal to international investors and economic actors. This, in turn, helps attract capital flows and improves the level of sustainable development.

2.2 Literature review

Empirical evidence on the impact of Green Economic Growth (GEG) on Sustainable Development (SD) is growing. Pan et al. (2019) assessed China's green economy, constructing a green productivity index based on the Global Malmquist–Luenberger index to measure its low-carbon transition. Using a Panel Vector Autoregressive (PVAR) model, their findings indicate that China achieved sustainable development through GEG between 2000 and 2016, underscoring the critical role of technological advancement. Lin and Zhou (2022) measured GEG within a sustainable development framework from 2000 to 2017, highlighting a mutually reinforcing relationship between the two concepts. By developing a comprehensive indicator system and applying the entropy-weighted TOPSIS method, they found that ecological health and social progress are central pillars of GEG, strongly supporting sustainable development. Their study also identified population size, economic development level, technological innovation, industrial structure, urbanization, environmental regulation, and Foreign Direct Investment (FDI) as influential factors, though their spatial impacts vary. Zeng et al. (2024) examined the effect of green energy on sustainable economic development and green recovery across 33 industrialized and developing nations from 1991 to 2022. Employing OLS, FEM, REM models and the Hausman test, their results confirm a positive contribution of green energy to SD, with population growth and GDP also exerting significant influences. Houssam et al. (2023) emphasized the green economy as a vital tool for sustainable development in both developed and developing countries. Focusing on 60 developing nations in 2018 and using the Generalized Least Squares (GLS) method with the Global Green Economy Index (GGEI), they found the green economy positively affects GDP and unemployment rates but may exacerbate poverty reduction challenges. The study advocates for promoting the green economy to meet sustainability goals. Finally, Li et al. (2024) investigated the role of natural resource management in fostering GEG for sustainable development in BRICS countries (2005-2014). Using a Propensity Score Matching with Difference-in-Differences (PSM-DID) model, they clarified the complex relationships between sustainability factors and green economy development. Their findings show that effective resource management positively impacts economic growth in BRICS nations, underscoring the green economy's supportive role in the sustainable development journey.

From reviewing the above literature, we identify several research gaps:

First, there is still limited research in the field of GEG. Previous studies have focused on separate effects and have not examined the interaction within a combined index. This leaves a notable gap in understanding the role of GEG in contributing to and improving sustainable development. This study builds a measurement index for green economic growth and then evaluates its impact on sustainable development.

Second, unlike previous studies that primarily used frequency-based models, this research aims to evaluate the impact of GEG and FD on sustainable development through a Bayesian regression model (probability-based). Bayesian regression techniques allow researchers to elucidate the influence of GEG and FD. A notable challenge is the high correlation in assessing these factors, which easily leads to multicollinearity. This explains why previous studies have rarely explored this relationship. Bayesian regression offers a powerful solution to challenges related to multicollinearity and uncertainty (Kruschke, 2015; McElreath, 2020). This approach provides a more nuanced understanding of how GEG and FD interact within contexts of environmental degradation, paving the way for more effective policy recommendations.

Furthermore, previous methods often aggregated information based on averages and percentages, without considering the uncertainty associated with the estimates. This situation can lead to biased and inconsistent research results that do not align with the actual variation of factors affecting sustainable development. In contrast, in Bayesian regression, each parameter is represented by a probability distribution (Le Quoc, 2024). This allows researchers not only to estimate the parameter's value but also to describe the uncertainty associated with this value. In the context of sustainability modeling, this is particularly important because sustainable development can be influenced by many unobservable factors or factors that change over time, such as policy volatility, technological change, or unexpected macroeconomic shocks. Bayesian regression is a method that allows researchers to adjust or update their estimates over time by modifying the probability distribution (McElreath, 2020). This not only provides a clearer view of the impact of GEG and FD on sustainable development but also shows the reliability of the estimates, thereby enabling more accurate policy decisions.

Through this, the study contributes to the academic literature in the following aspects: First, the study clarifies the impact of GEG and FD on sustainable development. Second, the study applies the Bayesian regression method to model sustainable development, helping to describe the uncertainty and fluctuation of influencing factors. Third, the study provides detailed insights into GEG and FD policies aimed at increasing sustainable development.

3 METHODOLOGY

3.1 Data and variable construction

The dataset encompasses 50 countries worldwide, selected based on data availability for the period from 2004 to 2021. Data for Sustainable Development (SD) was collected from the Center for Sustainable Development Goals Transformation. Meanwhile, data for Green Economic Growth (GEG) were compiled from the World Bank (World Development Indicators - WDI) and the Organization for Economic Cooperation and Development (OECD).

Based on the aforementioned rationale, the model examining the impact of GEG on SD is established as follows:

$$SD_{i,t} = \beta_o + \beta_1 GEG_{i,t} + \beta x X_{i,t} + \varepsilon_{i,t} \qquad (1)$$

Sustainable Development (SD) is widely utilized as an effective framework for assessing the level of economic sustainability. This metric is implemented based on 17 indicators linked to the three core pillars of sustainable development: a sustainable economy, a sustainable society, and a sustainable environment. This measure has been extensively applied in prior research, such as Dhahri et al. (2024), Ahmad et al. (2024), and Zeng et al. (2024); Dinh (2025a, 2025b 2025c 2025d); Kim & Quoc (2024); Khoi &

Dinh (2025); Huy et al (2025a, 2025b). The index serves as a robust tool, affirming its reliability and relevance in sustainable development research.

A review of the literature reveals a consensus that Green Economic Growth (GEG) cannot be captured by a single indicator. Instead, it must be measured as a composite of multiple variables reflecting its diverse scope, including aspects of the green economy, energy resources, education, and related metrics. Following this approach, we construct the GEG variable from 19 constituent indicators: (1) Renewable energy consumption (FEC); (2) Renewable electricity production (ELC); (3) CO2 emissions (CO2); (4) Forest area ratio (FRST); (5) Total resource rents (TOTL); (6) Freshwater withdrawals (H2O); (7) Energy intensity (PIMW); (8) Damage from resource extraction (DRES); (9) Damage from particulate matter (DPEM); (10) Net forest loss (DFOR); (11) Damage from CO2 emissions (DCO2); (12) Energy resource depletion (DNGY); (13) Mineral depletion (DMIN); (14) Total greenhouse gas emissions (GHG); (15) Environmental taxes (TAX); (16) Investment in education (AEDU); (17) Gross national savings (GNS); (18) Fixed capital consumption (DKAP); (19) Renewable combustible energy and emissions (CRNW). These indicators are fundamental to constructing the composite GEG (Huy & Loan, 2022, Huy et al., 2023a, Huy et al., 2023b, Huy & Tam, 2025; Le Quoc et al., 2024; Nguyen Quoc et al., 2025; Nga et al., 2024a, Nga et al., 2024b).

In this context, the GEG index is synthesized using Principal Component Analysis (PCA), a powerful tool for reducing data dimensionality (Jackson, 2005). The goal of this method is to extract principal components that are closely associated with the variation in the original variables through data transformation (Oanh & Dinh, 2024a, 2024b). The original variables were reduced to six principal components with eigenvalues exceeding 1, collectively explaining 71.96% of the total variance. Eigenvalues and eigenvectors provide details on the importance of each indicator. If the variance explained by the first principal component (PC1) exceeds 70%, it is used alone to compute the composite index. However, if multiple principal components (PCs) are retained, the composite index is calculated as a weighted sum of these PCs, using their variance explained ratios as weights (Kurniawan et al., 2025). In this study, selecting only PC1 would result in a significant loss of information. Therefore, we decided to combine multiple principal components to construct a single composite index that retains most of the explanatory information while effectively measuring GEG. The cut-off point was determined by applying a cumulative variance explained threshold of over 70% and retaining components with eigenvalues greater than 1.

Table 1

Probabilistic contributions of the variables

Dim	Eigenvalue	Proportion	Cumulative
Dim 1	4.54523	0.2273	0.2273
Dim 2	3.80008	0.1900	0.4173
Dim 3	2.00043	0.1000	0.5173
Dim 4	1.58608	0.0793	0.5966
Dim 5	1.40764	0.0704	0.6670
Dim 6	1.05342	0.0527	0.7196
Dim 7	0.99334	0.0497	0.7693

Source: Authors' calculation

As shown in Table 1, we aggregated the principal components (PCs) into a single composite index for measuring GEG, using the variance explained ratios as weights. This method helps retain most of the information from the original variables and has been widely used in previous studies, such as Fernandez & Martos (2020), Zheng & Chen (2024), and Chao & Wu (2017). However, to ensure the validity of the PCs before aggregation, orienting the PCs toward a positive direction is essential (Jain & Mohapatra, 2023); this method reflects a positive orientation toward the green economy. Boudt et al. (2022) emphasize that reorienting the PCs according to an important variable or a positive policy variable makes the composite index easier to interpret while preserving the statistical integrity of the PCA. Consequently, the general formula for aggregating the component PCs is established as:

$$CI = \sum_{i=1}^{k} \pi_i Y_i \qquad (2)$$

in there:

CI: Composite Index.

πi: Variance explained ratio of PCi.

k: Number of retained principal components.

Yi: Principal component PCi.

Based on the above reasoning, the GEG score is calculated using the following formula:

GEG = 0,2273PC_1 + 0,1900PC_2 + 0,1000PC_3 + 0,0793PC_4 + 0,0704PC_5 + 0,0527PC_6 (3)

Based on the above rationale, we propose the following hypotheses:

Hypothesis H1*: Green Economic Growth (GEG) enhances Sustainable Development.*

In addition to the two main independent variables, this study includes five control variables: Foreign Direct Investment (FDI), Urbanization Rate (UR), Population Growth (POP), Inflation Rate (INF), and Unemployment Rate (UNE). These control variables are crucial for reducing model error, increasing estimation accuracy, and strengthening the identified impact of GEG on sustainable development.

3.2 Research model

In addition, the Bayesian approach is also capable of mitigating model-related issues such as endogeneity, heteroscedasticity, and autocorrelation (Thach, 2020).

From a Bayesian perspective, we construct a linear regression using probability distributions as follows:

$$y \sim N(\beta^T X; \sigma^2 I) \quad (4)$$

Where the mean and variance of a normal distribution are used to get the value y. The displacement of the weight matrix times the prediction matrix is the linear regression mean. The variance is calculated by multiplying the identity matrix by the square of the standard deviation (σ).

The model parameters are presumed to originate from the probability distribution, in addition to the output (y) being generated from it. Based on the inputs and outputs, the posterior probability of the conditional model parameters has the following form:

$$P(\beta|y, X) = \frac{P(y|\beta, X)(P(\beta|X)}{P(y|X)} \quad (5)$$

In there:

P(β|y,X): Posterior distribution of model parameters given inputs and outputs

P(y|β,X): Likelihood of the data

P(β|X): Prior probability distribution

P(y|X): Normalizing constant that can be ignored

As a result, equation (2) is frequently reduced to:

$$P(\beta|y,X) = P(y|\beta,X)(P(\beta|X) \qquad (6)$$

Bayesian regression was used in the procedure to evaluate the impact of Green Economic Growth (GEG) on Sustainable Development (SD) through a specific three-step process: First, to ensure the recorded estimates tend toward zero rather than away from it, and to avoid biasing the analysis in a positive or negative direction, prior distributions for the regression coefficients were established with a mean assumption of zero. For the next step of the process, based on the parameters extracted from the equation, the distribution for the likelihood functions of the coefficients was determined. The final step was to obtain the posterior distribution of the coefficients by applying Markov Chain Monte Carlo (MCMC) and Gibbs Sampler techniques. This was done through a process of estimating and simulating 30,000 samples based on the posterior distribution, with the first 5,000 samples removed. MCMC techniques are widely applied to refine complex models in various fields (Levy & Mislevy, 2017; Quoc et al., 2025a; Quoc et al., 2025b; Quoc et al., 2025c; Van et al., 2025a, Van et al., 2025b, Tuyet & Dinh, 2025).

4 RESULTS

4.1 Descriptive statistics overview

SD has a mean value of 70.45 and a standard deviation of 9.43, indicating significant variation across countries, with diverse distribution characteristics. The minimum value is 45.17 and the maximum is 86.86. This reflects that some countries have relatively low SD indices while others are at a robust level of sustainability. GEG index has a mean of 0.7589 and a standard deviation of 0.1285, suggesting that most countries exhibit a moderate level of green economic growth. The minimum value of 0 indicates that some nations have not yet pursued a green growth trajectory, while the maximum value of 1 reflects strong green economic growth in others.

Table 2

Descriptive Statistics

Variable	Mean	Std. Dev	Minimum	Maximum
SD	70.4561	9.4348	45.1705	86.8687
GEG	0.7589	0.1285	0,0000	1,0000
FDI	5.3884	13.9510	-117.3747	234.2487
POP	0.8853	1.0456	-2.2584	3.4964
UNE	7.2191	4.3737	0.398	26.094
INF	4.2843	4.7571	-4.4781	51.4608
UR	64.1336	18.2559	16.507	95.515

Source: Authors' calculation

4.2 Bayesian results

The Bayesian regression results for 50 countries are detailed in Table 3, specifying the key insights. The results show the mean values of the variables are presented clearly, differing from the approach of regression coefficients in traditional regression methods. In the Bayesian method, the "mean" represents the expected value of the parameter after considering the model's probability distribution, whereas the "regression coefficient" in traditional frequency methods provides only a single parameter value without considering estimation uncertainty. Specifically, the results show the means of the variables GEG is 0.24, respectively, which can be interpreted as average estimates indicating the degree of influence of these factors when applying the Bayesian method. These values reflect the probability distribution of the parameters and are not single values as in conventional regression.

The diagnostic tests for the Bayesian regression model show an average acceptance rate of 0.3471, which falls within the stable range of 0.2 to 0.5. The efficiency min of the MCMC chains all exceeds the allowable threshold of 0.01, indicating that the sampling process is sufficiently diverse to accurately estimate the target distributions. The posterior distribution constructed via MCMC techniques must ensure that the obtained sample represents the target distribution. Therefore, MCMC diagnostic tools are essential for testing the convergence of the Markov chains and determining the sampling stopping point. In this study, the author uses the Gelman–Rubin statistic ($\hat{R}c$ coefficient) to assess convergence and the efficiency index to examine sampling quality. The results in Table

3 show that the Rc value is less than 1.1, meeting the convergence criterion according to Levy (2020). Simultaneously, all efficiency indices are greater than 0.01, demonstrating the stability and high reliability of the MCMC estimation. Unlike traditional statistical methods such as OLS, FEM, or REM, which often rely on a p-value < 0.05 to determine statistical significance, the Bayesian method uses Monte Carlo Standard Error (MCSE) to assess the accuracy of the estimation. MCSE measures the error between the MCMC chain estimate and the true value of the target distribution, rather than relying solely on p-values. According to Flegal et al. (2008), as MCSE approaches zero, the stability of the MCMC chain increases; an MCSE below 6.5% of the standard deviation is considered acceptable, and below 5% is optimal. Based on the analysis results in Table 3, all variables in the model meet this criterion. In this context, the MCMC diagnostic indicators-acceptance rate, efficiency, $\hat{R}$c coefficient, and MCSE all exceed the required thresholds, confirming the robustness and reliability of the Bayesian simulation results in this study.

Table 3

Results Bayesian

Dependent Variable: SD	**50 Countries**				
	Mean	**Std. Dev.**	MCSE	95% Credible Interval	
GEG	0.2401	0.0188	0.0002	0.2031	0.2769
FDI	0.0076	0.0166	0.0003	-0.0253	0.0402
UNE	-0.0767	0.0180	0.0002	-0.1119	-0.0414
POP	-0.4345	0.0199	0.0002	-0.4734	-0.3952
INF	-0.1537	0.0185	0.0002	-0.1900	-0.1175
UR	0.3941	0.0198	0.0003	0.3554	0.4330
C	-0.0000	0.0164	0.0000	-0.0322	0.0323
Average acceptance rate			0.3471		
Efficiency: min			0.0215		
Gelman-Rubin ($\hat{R}$)			1.0020		

Source: Authors' calculation

Table 4

Probability of impact

Probability	**71 Countries**		
	Mean	Std. Dev	MCSE
{SD: GEG} > 0	1.0000	0.0000	0.0000
{SD: FDI} > 0	0.6764	0.4678	0.0046
{SD: UNE} < 0	0.9999	0.0031	0.0000
{SD: POP} < 0	1.0000	0.0000	0.0000
{SD: INF} < 0	1.0000	0.0000	0.0000
{SD: UR} > 0	1.0000	0.0000	0.0000
{SD: CONS} > 0	0.5008	0.5000	0.0050

Source: Authors' calculations

4.3 Discussion

The Bayesian regression results for 50 countries worldwide from 2004 to 2021 are presented in detail in Table 3, highlighting the key findings. As emphasized earlier, Green Economic Growth (GEG) has a positive impact on Sustainable Development (SD) with probability 100% (Table 4). GEG holds significant potential in advancing the sustainability agenda, underscoring its importance in enhancing SD-particularly in boosting social and environmental benefits while stimulating economic activity. This role is widely acknowledged amidst growing concerns over climate change and environmental degradation. GEG fosters harmony between a nation's economic progress, social well-being, and ecological health. Even for countries experiencing fluctuations in their sustainable development trajectory, GEG facilitates progress by improving resource-use efficiency, reducing costs, and promoting social equity. Furthermore, GEG strengthens ecosystem resilience, curbs environmental degradation, and thereby supports the sustainable development journey. These findings extend and reinforce the existing body of literature, particularly when compared with prior studies such as Pan et al. (2019), Lin and Zhou (2022), Zeng et al. (2024), Houssam et al. (2023), and Li et al. (2024), which have examined the broader impacts of a green economy on SD. While earlier research established a general linkage between the green economy and SD, this study focuses specifically on the growth dimension of the green economy, offering deeper insights into how environmental improvements can enhance sustainability in modern economies. By shifting the focus to GEG, this research provides a more nuanced and contemporary perspective on the role of greening the economy in the sustainability transition, especially for economies increasingly reliant on green growth strategies. These results strongly support Hypothesis 1 (H1), which posits that GEG positively influences SD. This alignment is consistent with established theoretical frameworks in the field, including Porter's Hypothesis (Porter and Linde, 1991; 1995), Disclosure Theory (Diamond and Verrecchia, 1991), and Signaling Theory (Spence, 1973). These theories suggest that GEG plays a pivotal role in improving sustainable development outcomes. By providing transparent information about resource and energy use and by minimizing emissions-factors that are essential for ensuring sustainability-GEG can significantly enhance SD. Therefore, GEG not only drives economic growth and environmental sustainability but also helps ensure that economic opportunities become more accessible to a broader range of nations.

To ensure that Bayesian inference based on the Markov Chain Monte Carlo (MCMC) sample is valid, the author tests the convergence of the MCMC parameter estimates through visual diagnostic plots. According to Balov (2020), MCMC convergence diagnostic plots include trace plots and posterior distribution plots. These plots help track the history of parameter values through consecutive iterations of the chain. Appendix 2 displays the convergence diagnostic results for the two variables GEG and FD impacting SD. The results indicate that all parameter plots in the model are reasonable, with consistent trace plot shapes and posterior distribution plots showing normal distributions, confirming the robustness of the Bayesian regression.

5 CONCLUTIONS

Faced with the threat of destruction from the "brown economy", sustainable development has become a required direction for countries around the world. In this context, green economic growth is considered an essential tool in strategies aimed at sustainable development. This study examines the impact of green economic growth on sustainable development in 50 countries from 2004 to 2021. Using the Bayesian regression method, we find that green economic growth increases sustainable development. These results show that green economic growth plays an important role in strengthening sustainable development, with a positive and statistically significant impact. This highlights the importance of green economic growth in improving global sustainable development and shows its potential to enhance economic conditions by increasing resource efficiency, reducing emissions and costs, and supporting entrepreneurship and economic inclusion. This study provides useful insights into the impact of green economic growth in the sustainable development process. It emphasizes the importance of implementing balanced policies to maximize the benefits of green economic growth. The findings contribute to the ongoing discussion about how to integrate the green economy into the broader economic framework in a strategic way in order to promote inclusive growth and move toward a sustainable economy. By addressing the research question, this study not only adds empirical evidence on the role of green economic growth in the environmental economy but also provides actionable insights for policymakers and researchers who aim to support sustainable economic development. Based on these findings, we recommend that countries focus on expanding and encouraging green economic growth through long term green economic strategies, reforms in environmental policies such as carbon pricing, and improving transparency in information about resources, sustainability reports, and actions that strengthen the circular economy. In addition, it is necessary to promote green technology through energy saving and encourage more firms to apply clean technologies. In this context, expanding green economic growth becomes a more effective strategy to address sustainability challenges and improve economic stability.

However, an important point is that no single policy is suitable for all countries or for every stage of development. Instead, designing the most appropriate policies requires a deep understanding of how green economic growth affects sustainable development. Applying flexible and well targeted policies will help countries create opportunities for development and international integration. One limitation of this study is that the green economic growth index could be improved by including more related variables such as green finance, innovation initiatives, or other indicators related to green economic growth. In future studies, the authors plan to expand the scope of green economic growth or apply different approaches in order to propose policies that fit current conditions.

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APPENDIX

Appendix 1

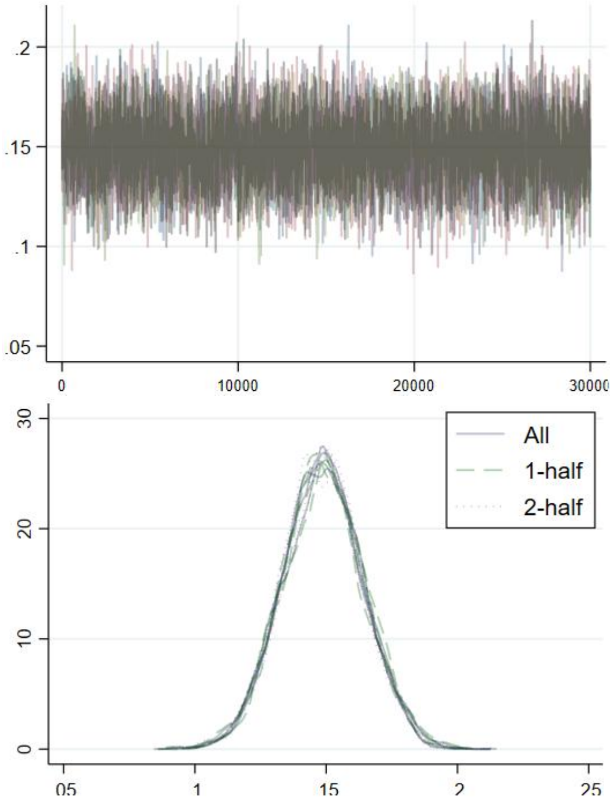
Variable Description and Sources

Code	**Indicator**	Measurement	Source
Dependent Variable			
SD	Sustainable Development	Calculated based on 17 indicators linked to the three main pillars of sustainable development: sustainable economy, sustainable society, and sustainable environment.	SDGs
Independent Variables			
GEG	Green Economic Growth	In this study, we use PCA technique to measure the GEG composite index. (All component variables were standardized before Principal Component Analysis).	Authors
1. FEC	Renewable Energy	Share of renewable energy in total final energy consumption (%)	WDI
2. ELC	Renewable Electricity	Share of electricity generated from renewable sources in total electricity production (%)	WDI
3. CO2	CO2 Emissions	CO_2 emissions per unit of GDP (2021 PPP $)	WDI
4. FRST	Forest Area Ratio	Proportion of forest area (natural and planted) to total land area (%)	WDI
5. TOTL	Total Resource Rents	Total natural resource rents (% of GDP)	WDI
6. H2O	Freshwater Withdrawals	Annual freshwater withdrawals as a proportion of total internal water resources (%)	WDI
7. PRIW	Energy Intensity	Primary energy consumption per unit of GDP	WDI
8. DCO2	Damage from CO2 Emissions	Monetary value of damage caused by CO2 emissions (% of GNI)	WDI
9. DRES	Damage from Resource Extraction	Depletion of natural resources, including energy, mineral, and forest resources (% of GNI)	WDI

10. DPEM	Damage from Particulate Matter	Monetary value of damage caused by exposure to PM2.5 air pollution (% GNI).	WDI
11. DFOR	Net Forest Depletion	Monetary value of forest resource depletion due to deforestation (% GNI)	WDI
12. DNGY	Energy Resource Depletion	Monetary value of energy resource extraction (oil, natural gas, coal) exceeding sustainable levels (% of GNI)	WDI
13. DMIN	Mineral Depletion	Monetary value of mineral extraction (% GNI).	WDI
14. GHG	Total Greenhouse Gas Emissions	Total greenhouse gas emissions (Mt CO_2e), including CO_2, CH_4, N_2O, and F-gases, per capita.	WDI
15. TAX	Environmental Taxes	Environmental tax revenue (% of GDP)	OECD
16. AEDU	Investment in Education	Public spending on education (% of GNI)	WDI
17. DKAP	Fixed Capital Consumption	Consumption of fixed capital, reflecting the depreciation of assets used in production (% of GNI)	WDI
18. GNS	Gross National Savings	Gross national savings, calculated as national income minus consumption plus net transfers (% of GDP)	WDI
19. CRNW	Renewable Combustibles & Waste	Share of energy from renewable combustibles and waste (% of total energy)	WDI
Control Variables			
UNE	Unemployment Rate	The share (%) of the total labor force that is unemployed and actively seeking employment.	WB
INF	Inflation Rate	The annual percentage change in the Consumer Price Index (CPI).	WB
UR	Urban Population	Urban population as a percentage of the total population.	WB
FDI	Foreign Direct Investment	Net inflows of foreign direct investment (% of GDP).	WB
POP	Population Growth Rate	The annual population growth rate (%).	WB

Appendix 2

Posterior Distribution and Trace Plots for Geg and SD



Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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