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UNVEILING THE IMPACT OF GREEN ECONOMIC GROWTH AND FINANCIAL DEVELOPMENT ON THE GLOBAL SUSTAINABLE DEVELOPMENT PATH: A BAYESIAN REGRESSION APPROACH

REVELANDO O IMPACTO DO CRESCIMENTO ECONÔMICO VERDE E DO DESENVOLVIMENTO FINANCEIRO NO CAMINHO DO DESENVOLVIMENTO SUSTENTÁVEL GLOBAL: UMA ABORDAGEM DE REGRESSÃO BAYESIANA

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Abstract
Climate change is not only a challenge but also affects the path toward sustainable development. The transition of the economy from brown to green relies on essential tools in this process, including green economic growth and financial development. However, until now no study has examined the simultaneous impact of green economic growth and financial development on sustainable development. This study seeks to address this gap by investigating the effects of green economic growth and financial development on sustainable development in 71 countries during the period from two thousand and four to two thousand and twenty one. Using the Bayesian regression approach, the results show that green economic growth has a positive effect on sustainable development (0.148), which reflects the importance of green economic growth in enhancing sustainable development across countries. Financial development also exerts a positive effect on sustainable development (0.274), indicating that a strong financial system with a large number of financial institutions enables firms and individuals to access resources and supports progress toward

Resumo
As mudanças climáticas não são apenas um desafio, mas também afetam o caminho para o desenvolvimento sustentável. A transição da economia de combustíveis fósseis para uma economia verde depende de ferramentas essenciais nesse processo, incluindo o crescimento econômico verde e o desenvolvimento financeiro. No entanto, até o momento, nenhum estudo examinou o impacto simultâneo do crescimento econômico verde e do desenvolvimento financeiro sobre o desenvolvimento sustentável. Este estudo busca preencher essa lacuna, investigando os efeitos do crescimento econômico verde e do desenvolvimento financeiro sobre o desenvolvimento sustentável em 71 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 sobre o desenvolvimento sustentável (0,148), o que reflete a importância do crescimento econômico verde para o aprimoramento do desenvolvimento sustentável em diversos países. O desenvolvimento financeiro também exerce

sustainability goals. These findings highlight the need to promote green economic growth as a key strategy while improving and upgrading the financial system to achieve sustainable development.

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

um efeito positivo sobre o desenvolvimento sustentável (0,274), indicando que um sistema financeiro robusto, com um grande número de instituições financeiras, permite que empresas e indivíduos acessem recursos e apoia o progresso em direção às metas de sustentabilidade. Essas descobertas destacam a necessidade de promover o crescimento econômico verde como uma estratégia fundamental, ao mesmo tempo em que se aprimora e moderniza o sistema financeiro para alcançar o desenvolvimento sustentável.

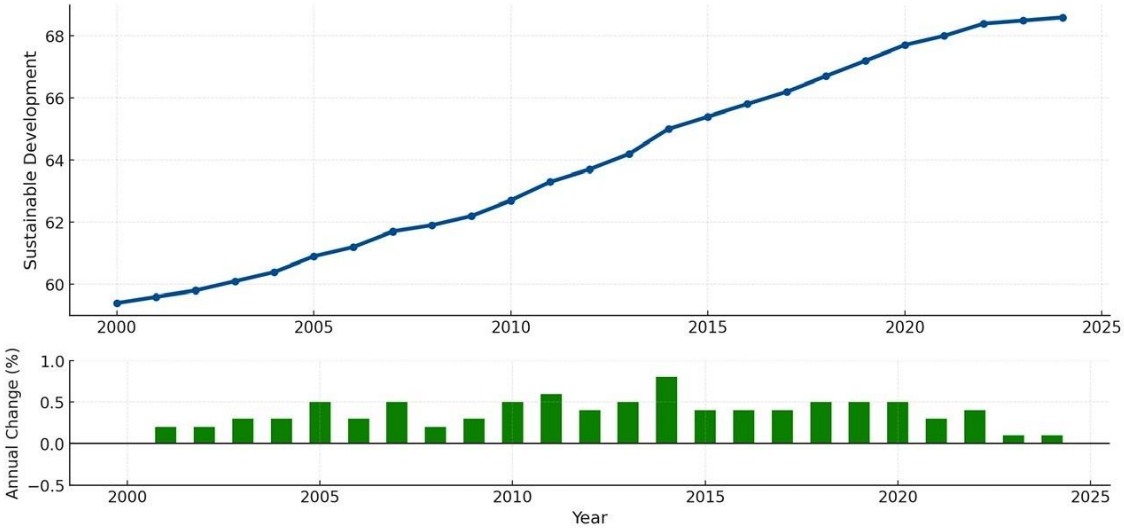
Palavras-chave: *Crescimento Econômico Verde. Desenvolvimento Financeiro. Desenvolvimento Sustentável. Regressão Bayesiana.*

1 INTRODUCTION

Environmental issues are global challenges that require appropriate measures and tools to address without hindering economic growth (Kwilinski & et al, 2023). In response to this situation, the European Commission adopted the European Green Deal (European Commission,2019) which establishes a framework for achieving carbon-neutral economic growth. At this time, the global economy is undergoing a profound transition. The structural shift from a 'brown' to a 'green' economy necessitates a reorientation of national economic development towards green principles. According to the Sustainable Development Goals (SDGs), economic growth needs to be accompanied by a transition to carbon neutrality and the reduction of greenhouse gas emissions (Pan & et al, 2019). In this context, Green Economic Growth aims to maximize resource efficiency and the productivity of inputs (labour, capital, energy, land, and education), minimize greenhouse emissions, and at the same time, lessen the negative impacts on the natural environment. Green Economic Growth has become an essential factor in fostering sustainable development and addressing social equity issues (Armutcu & et al, 2024). Furthermore, Green Economic Growth might result in substantial economic, societal, and environmental benefits (Lin & Zhou, 2022). Green Economic Growth represents a model for sustainable economic development by fostering coherence between economic growth, social harmony, and environmental improvement.

Figure 1

The charts below show sustainable development growth tendencies.



Source: Sustainable Development Goals – SDGs

Figure 1 illustrates the global average sustainable development index from 2000 to 2024. Overall, the level of global sustainability showed an upward trend over the period, indicating that countries worldwide are increasingly focusing on achieving sustainable development. In response to the demand for sustainable development (SD), the United Nations has affirmed the essential role of financial development (FD) in poverty reduction and the advancement of the Sustainable Development Goals (SDGs). In the 2030 Agenda, the UN emphasizes that FD enhances financial access, mobilizes capital, and expands financial inclusion, thereby helping to address inequality and support sustainable growth (Khemani & et al, 2023). This demonstrates the significant benefits of FD in the pursuit of sustainable development. In particular, the economies that possess a solid financial system, with a large number of financial organisations will benefit individuals and enterprises (Hai & Dinh, 2024), especially businesses that are small and easily accessible to funding; thereby promoting business production and facilitating sustainable goals (Dhahri& et al, 2024; Huy & Loan, 2022; Huy et al, 2024, Huy et al., 2023a; Huy et al., 2023b; Huy & Tam, 2025). By contrast, in some countries where there is lower financial development, expanding the demand for multifaceted financial accessibility is still highlighted to be the key element that should be prioritized to promote consumption and social improvements; thereby incentivizing sustainable development (Dong & et al, 2024). These differences underscore the role of FD in the sustainable journey, leading us to conclude that examining the impact of financial development is indispensable. This research aims to address the important question of how Green Economic Growth (GEG) and Financial Development (FD) impact sustainable development globally. The significance of this issue lies in the sustainable journey and its potential to reshape the economic landscape. Therefore, in this research, we focus on answering two main questions : (1) In which way will Green Economic Growth (GEG) and financial development impact sustainable development? And also, (2) in which policies will Green Economic Growth (GEG) and financial development be promoted by countries in the current sustainable era?

2. TTHEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Theoretical foundation

Theoretical frameworks for the impact of Green Economic Growth (GEG) and Financial Development (FD) on 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. Concurrently, Financial Development plays an essential role in supporting environmental policies by mobilizing resources for green businesses to scale up, thereby ensuring the feasibility of achieving sustainability goals.

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. Furthermore, Financial Development (FD) accelerates green economic expansion by reducing the costs associated with information disclosure. It plays a critical role in enabling Small and Medium-sized Enterprises (SMEs) to learn about clean technologies and access necessary funding. This not only stimulates economic growth and reduces inequality but also ensures a higher likelihood of achieving Sustainable Development Goals.

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. Financial development (FD) plays a particularly vital role in facilitating this structural transformation towards sustainability. FD improves access to capital, which empowers individuals and businesses, particularly Small and Medium-sized Enterprises (SMEs), to participate in productive economic activities. This empowerment is a fundamental driver 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.

Financial Development (FD) has consistently been a critical strategy for supporting sustainable development. Dong et al. (2024) examined the relationship between FD, CO2 emissions, and sustainable development across 30 Chinese provinces from 2005 to 2021. Using a PVAR model, a Fixed Effects (FE) model, and the entropy weight method, their findings indicate that FD positively impacts sustainable development. However, CO2 emissions were found to exacerbate challenges to sustainability, implying that both FD and carbon emissions play significant roles in shaping a sustainable economy. Dhahri et al. (2024) evaluated the impact of information technology and FD on Sustainable Development Goals (SDGs) using data from 48 countries in Sub-Saharan Africa. Employing a system GMM model, the results demonstrate that both FD and information technology positively enhance economic, social, and environmental sustainability. Ahmad et al. (2024) investigated the relationship between FD, resource abundance, eco-innovation, and sustainable development in OECD countries from 1990 to 2019. By applying the Common Correlated Effects Mean Group (CCEMG) estimator, their results reveal that FD and eco-innovation have a positive and statistically significant effect on sustainable development. In contrast, natural resource rents negatively impact sustainability, confirming the existence of the "resource curse" hypothesis in these nations. Khemani and Kumar (2023) explored whether FD is a key factor in achieving the 2030 Agenda for Sustainable Development. Analyzing 35 Asian countries based on sustainable development trends using an ordered probit model, they found that FD accelerates progress toward sustainability. A subsequent pairwise Granger causality test further examined the causal relationship between sustainable development and FD. Finally, Ziołо et al. (2023) examined the relationship between sustainable development and FD in European Union countries. Applying a fuzzy logic approach, their results show that a higher level of sustainable development is associated with a greater financial development index, highlighting the role of financial markets as drivers of financial development.

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

First, to date, no study has simultaneously assessed the combined impact of Green Economic Growth (GEG) and Financial Development (FD) on Sustainable Development (SD). Previous studies have focused on their individual impacts without exploring the interaction or joint influence of these two factors. This leaves a significant gap in understanding *how* GEG and FD, when considered together, contribute to and enhance 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, Dinh, 2025a; Dinh, 2025b; Dinh, 2025c; Dinh 2025d; Kim & Quoc, 2024; Khoi & Dinh, 2025; Huy & Dinh, 2025a; Huy & Dinh, 2025b). 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; Nguyen Quoc et al., 2025; Quoc et al., 2025a, Quoc et al., 2025b; Quoc et al., 2025c; Quoc & Quoc, 2025). 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; Oanh & Ha, 2025; Van et al., 2025a; Van et al., 2025b; Tuyet & Dinh, 2025; Van & Le Quoc, 2025). 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 RESEARCH AND METHODOLOGY

3.1. Data and variable construction

The dataset encompasses 71 countries worldwide, selected based on data availability for the period from 2004 to 2021. Data for Sustainable Development (SD) was collected from the Sustainable Development Solutions Network (SDSN). Meanwhile, data for Green Economic Growth (GEG) and Financial Development (FD) were compiled from the World Bank's World Development Indicators (WDI) and the International Monetary Fund (IMF).

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

$$SD_{i,t} = \beta o + \beta 1GEG_{i,t} + \beta 2FD_{i,t} + \beta x X_{i,t} + \varepsilon_{i,t} \qquad (1)$$

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). 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 index.

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	Percentage	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.
π_i: Variance explained ratio of PC_i.
k: Number of retained principal components.
Y_i: Principal component PC_i.

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

$$GEG = 0{,}2273PC_1 + 0{,}1900PC_2 + 0{,}1000PC_3 + 0{,}0793PC_4 + 0{,}0704PC_5 + 0{,}0527PC_6$$

The construction of the Financial Development (FD) index is a methodologically rigorous process, utilizing 105 indicators from the Global Financial Development Database (GFDD**)** and 46 indicators from FinStats. These indicators are classified into sub-indices, such as: Financial Institution Depth (FID), Financial Institution Access (FIA), Financial Institution Efficiency (FIE), Financial Market Depth (FMD), Financial Market Access (FMA), and Financial Market Efficiency (FME). This comprehensive index captures both the institutional and market dimensions of FD. Aggregating these sub-indices into a single FD index ensures a holistic representation of the financial system's structure and functionality. This index is particularly relevant for analyzing its impact on SD. A robust financial system contributes to enhanced sustainable development by expanding the number of substantial financial institutions. This expansion facilitates access to financial resources for individuals and businesses, thereby improving the capacity to achieve SD goals. Conversely, in contexts with low levels of financial development, the demand for broad-based financial access remains a critical factor for stimulating consumption, production, and welfare improvement, which in turn supports sustainable development.

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

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

Hypothesis H2: *Financial Development (FD) 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 and FD on sustainable development.

3.2. Research model

The research model is as follows:

$$SD_{i,t} = \beta_o + \beta_1 GEG_{i,t} + \beta_2 FD_{i,t} + \beta_x X_{i,t} + \varepsilon_{i,t} \qquad (3)$$

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:

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

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 (3) is frequently reduced to:

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

Bayesian regression was used in the procedure to evaluate the impact of Green Economic Growth (GEG) and Financial Development (FD) 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).

4. RESEARCH RESULTS

4.1 Descriptive statistics overview

SD has a mean value of 69.88 and a standard deviation of 9.67, 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 0.7432 and a standard deviation of 0.1367, 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. Financial Development (FD) has a mean of 0.4206 and a standard deviation of 0.2489, showing that the overall level of financial development across countries is relatively low but exhibits substantial dispersion. The minimum value of 0.065 reflects very low financial development in some countries, while the maximum of 0.9968 indicates superior financial development in others.

Table 2

Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
SD	69,88786	9,674445	45,17051	86,86873
GEG	0,743251	0,136742	0,000000	1,000000
FD	0,420653	0,248927	0,065680	0,996816
UNE	7,229059	4,365132	0,120000	28,77000
UR	63,54729	19,18372	16,50700	98,11700
POP	0,953690	1,061174	-4,25664	3,571097
INF	4,231917	4,448634	-4,47810	51,46086
FDI	6,291577	19,47186	-117,374	280,1455

Source: Authors' caculations

In addition, we conducted a correlation matrix test to assess the influence of variables in the dataset and evaluate the phenomenon of multicollinearity. The correlation matrix results are presented in Figure 4, summarizing the key insights. The test results show that the coefficients between the independent variables are all at low to moderate levels, with no variable pair exceeding the correlation threshold of 0.8 – the level of severe multicollinearity. This carries the important implication that the dataset does not exhibit severe multicollinearity, and all research variables can be included in the study model.

Table 3

Correlation matrix

	GEG	FD	FDI	POP	UNE	INF	UR
GEG	1,0000						
FD	0,4388	1,0000					
FDI	0,0612	0,0376	1,0000				
POP	-0,3145	-0,2634	0,0250	1,0000			
UNE	0,1675	0,1099	0,0264	-0,3187	1,0000		
INF	-0,3946	-0,4382	-0,0206	0,2395	-0,0892	1,0000	
UR	0,4535	0,6329	0,0254	-0,3850	0,2123	-0,3561	1,0000

Source: Authors' calculations

4.2 Bayesian regression results

The Bayesian regression results for 71 countries are detailed in Table 4, 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 and FD are 0.148 and 0.274, 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 0.3475, which falls within the stable range of 0.2 to 0.5. The lowest efficiency 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

4 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 4, 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 4

Bayesian Regression Results

Dependent Variable: SD	**71 Countries**				
	Mean	**Std. dev.**	MCSE	95% Credible Interval	
GEG	0,1486753	0,0153940	0,000239	0,1185476	0,1790948
FD	0,2747668	0,0176188	0,000338	0,2405032	0,3091365
FDI	0,0411610	0,0128321	0,000262	0,0157220	0,0664599
UNE	-0,0885117	0,0137749	0,000287	-0,1153190	-0,0615756
POP	-0,4506022	0,0147427	0,000268	-0,4803405	-0,4216557
INF	-0,0672094	0,0147637	0,000239	-0,0958626	-0,0382377
UR	0,2903964	0,0179079	0,000310	0,2554639	0,3257773
C	0,0000263	0,0129839	0,000078	-0,0254016	0,0255678
Average acceptance rate			0,8475		
Lowest efficiency			0,0164		
Maximum Gelman-Rubin ($\hat{R}$) statistic			1,0020		

Source: Authors' calculations

Table 5

Probability of impact

Probability	71 Countries		
	Mean	Std. Dev	MCSE
{SD: GEG} > 0	1.0000	0.0000	0.0000
{SD: GEG2} > 0	1.0000	0.0000	0.0000
{SD: FDI} > 0	0.9993	0.0258	0.0002
{SD: UNE} < 0	1.0000	0.0000	0.0000
{SD: POP} < 0	1.0000	0.0000	0.0000
{SD: INF} < 0	0.9999	0.0016	0.0000
{SD: UR} > 0	1.0000	0.0000	0.0000
{SD: CONS} > 0	0.5008	0.4999	0.0050

Source: Authors' calculations

4.3 Discussion of results

The Bayesian regression results for 71 countries worldwide from 2004 to 2021 are presented in detail in Table 4, highlighting the key findings. As emphasized earlier, Green Economic Growth (GEG) has a positive impact on Sustainable Development (SD) with probability 100% (Table 5). 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.

The results show that FD increases sustainable development with probability 100% (Table 5), which highlights the positive relationship between FD and sustainable development. In the context of environmental degradation, FD has a strong impact aimed at enhancing market economic value and a sustainable environment. Accordingly, in countries with high levels of financial development, such as Australia, Japan, France, Sweden, a solid financial system with many financial institutions helps businesses and economic entities, especially small and medium-sized enterprises (SMEs), easily access resources, ensuring the ability to achieve sustainable development goals. Conversely, in countries with low levels of financial development such as Burkina Faso, Cambodia, Cameroon, the demand for multidimensional financial access is still an important factor needed to promote consumption, production, and welfare improvement, thereby supporting sustainable development. Furthermore, a developed financial system helps reduce emissions and promote renewable energy. In addition, an efficient financial system helps minimize transaction costs, optimize resource allocation, and increase capital mobilization. Especially when businesses gain access to financial resources, it stimulates creative innovation and increases production, expanding the labor market. These findings show that FD plays an important role in the journey towards sustainable development. Therefore, managing FD in the context of environmental degradation requires a delicate balance, promoting innovation while ensuring the availability of economic opportunities that are easily accessible and inclusive in the context of the new era.

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 CONCLUSIONS

Under the threat of the destruction of the Brown economy, sustainable development has become a mandatory norm in countries around the world. Here, green economic development and financial growth are considered to be indispensable tools in the strategy aiming to sustainable development. This study assesses the impacts of green economic development and financial growth in the sustainable development journey of 71 countries from 2004 to 2021. By using the Bayesian regression, we realized that green economic development could promote sustainable growth. These results show that green economic development is crucial to enhance sustainable development, with its positive impacts and high level of statistical significance for sustainable development. This highlights the importance of green economic development in increasing global sustainable development, emphasizing the potentials to improve economic conditions by enhancing resource use efficiency, reducing costs and enhancing resource use efficiency, reducing emissions and costs, and promoting entrepreneurial spirit and economic inclusion, and also promoting entrepreneurial spirit as well as economic inclusion. Besides, financial growth also has powerful impacts on the sustainable journey , the result indicates that financial growth promotes sustainability through improving the ability to access and allocate financial resources. This helps businesses, especially small and medium-sized businesses (SMEs) easily raise funds and promote production, ensuring the ability to pursue sustainable development goals (SDGs). Thus, this study provides invaluable insights about the impacts of green economic development and financial growth in the journey of sustainable development. This study also emphasizes the significance of implementing balanced policies with an aim to optimize the benefits of green economic development and financial growth, especially in some countries where there are limited financial systems. These findings contribute to the existing discussion about strategic ways to put green economy and financial development into a larger economic framework, aiming to foster comprehensive growth and enhance sustainable development. By answering the question of the established research, this study not only adds empirical evidence about the role of green economic growth and financial development in the green economy but also provides practical insights for policy planners and researchers who are finding methods to promote a sustainable economy. Based on these findings, we suggest nations should focus on expanding and enhancing green economic development through long-term green economic growth strategy, environmental policy reform, such as carbon evaluation and calling for providing transparent information about resources, sustainable reports and promoting the circular economy. In addition, technological innovations should be carried out by saving energy and promoting the expansion of businesses adopting clean technologies. In term of financial development, there should be an enhancement in financial integration reducing social inequality, which offers disadvantaged groups and SMEs enterprises the accessibility to sources of capital. This will promote business production and guarantee the journey towards sustainable development goals. In this context, expanding green economic growth and financial development serve as effective strategies to tackle sustainable challenges and promote economic sustainability. However, one notable problem is that there is no specific policy that is appropriate to all countries or suitable in a developing period. Instead, planning the most appropriate policies needs to be based on in-depth understanding of how green economic development and financial growth impact on sustainable development. By adopting flexible and goal-oriented policies, nations can find opportunities to thrive and integrate into the global economy. One deficiency of the study is that the development of the green economic index (GEG) can be expanded by reinforcing other related variables, such as green finance, innovations or variables that are related to green economic development. In the next research, the authors have a plan to assess the extent of green economic development more extensively by applying other practices, with an aim to give policies that are suitable at the present situation.

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APPENDIX

Appendix 1

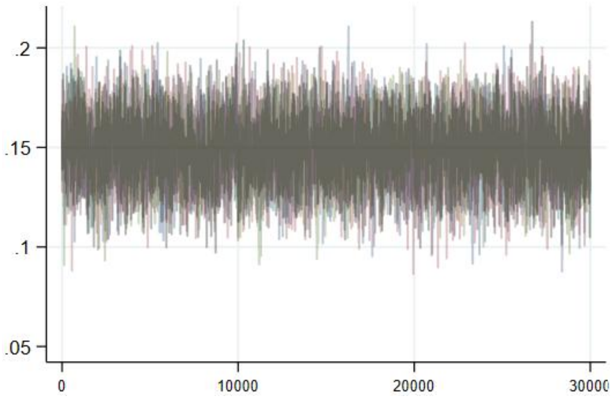
Variable Description and Sources

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

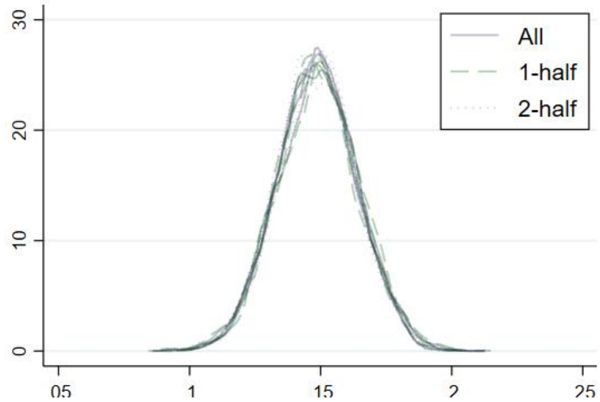
Appendix 2

Posterior Distribution And Trace Plots For GEG, FD And SD



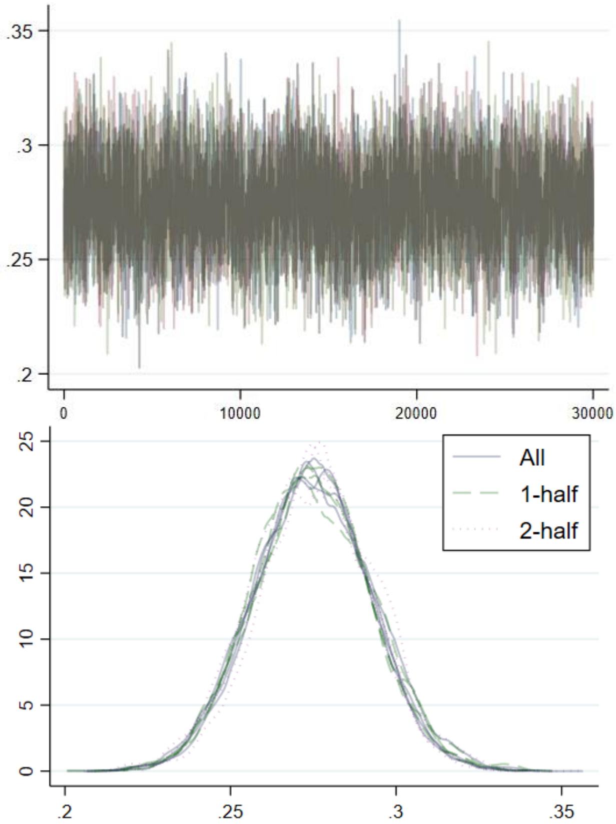
Appendix 3

Posterior Distribution and Trace Plots For SD And GEG



Appendix 3

Posterior Distribution and Trace Plots for SD and FD



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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