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Econometric Analysis of BRICS Countries' Activities in 1990–2022: Seeking Evidence of Sustainability

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Abstract: BRICS countries, which cause 43.2 percent of global greenhouse gas emissions, are crucial in the world's effort toward environmental sustainability. BRICS countries are among the world's largest maritime traders and account for a good share of carbon emissions through shipping and the degradation of marine ecosystems. This research provides a novel contribution by examining the combined effect of energy intensity, innovation, blue economy activities and renewable energy on environmental sustainability for the period between 1990 and 2022 for BRICS nations under the shadow of ESG—economic, social and governance readiness. The key variables are energy intensity, renewable energy usage, innovation, blue economy and ESG readiness, with a critical focus on the environmental consequences. By applying Driscoll and Kraay's robust adopting-type approach and panel quantile estimation, the findings indicate that adopting renewable energy and increased innovation significantly lowers GHG emissions across BRICS economies. The study further establishes that international ocean trade and fishing activities contribute to the deterioration of the environment through the overexploitation of resources and emissions resulting from shipping activities, with the consideration of these as the backbone of the blue economy. However, social and positive influences on sustainable practice in the BRICS region, as reflected through policy frameworks, economic development, and technical cooperation among members, positively influence the adoption of sustainable practices, thereby driving progress toward environmental goals. This study underlines the importance of continued technical cooperation among BRICS countries, with a commitment to sustainable innovation and a transition to renewable energy as essential strategies to reduce environmental degradation and enhance long-term sustainability.

Keywords: sustainability; BRICS; energy transition; renewable energy; environment; blue economy; international relations

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1. Introduction

The BRICS group, which includes Brazil, Russia, India, China and South Africa, was set up in 2010 to improve economic cooperation among these countries. The group represents 40% of the world's population and roughly a quarter of its GDP. Collectively, BRICS

countries contribute to about 14.6% of total imports and 18.2% of global exports [1]. The high trade of BRICS induces the massive production of goods and services [2]. BRICS stands out for its challenges—a high threat of corruption and economic and social inequalities [3]. These countries are also grappling with environmental issues stemming from their economic growth, industrialization and population expansion [4–6]. To meet trade demand and production, BRICS countries heavily depend on fossil fuel consumption for energy production [7–9]. Therefore, these countries are heavy emitters of greenhouse gases such as carbon dioxide, methane and nitrogen dioxide [10,11]. Ships used in ocean trade with BRICS countries are also responsible for causing high carbon emissions due to fossil fuel usage. Unsustainable ocean operations are a massive threat to marine life and people [12–14]. Therefore, the "blue economy", in other words, actions that promote sustainable human–ocean connections and, thus, improve ocean-based economic operations in the long- and short-run, have become important [15].

In addition, the BRICS countries (Brazil, Russia, India, China and South Africa) face many environmental challenges stemming from their rapid economic development, industrialization and population growth. The problems and challenges include air and water pollution, deforestation, climate change consequences, waste management issues and biodiversity loss [16]. In terms of Brazil, the main concern is deforestation because the Amazon rainforest is under significant threat due to logging, agricultural expansion and mining. Deforestation has accelerated in recent years all over the world, but especially in countries with weak political structures [17]; thus, this is leading to the loss of biodiversity and has an impact on carbon neutrality. Brazil hosts around 10% of the world's known species and habitat destruction has put many of these species at risk. In addition, another challenge is water pollution because industrial activities, mining and agriculture contribute to water pollution in Brazil's rivers [18]. Russia is the largest region in the world in terms of land area and, furthermore, a large part of its geography is very flat. Major cities in Russia suffer from high levels of air pollution due to industrial emissions and vehicle exhausts [19]. Furthermore, Russia faces challenges in managing industrial and municipal waste, leading to illegal dumping and contamination [20] which further impacts its water resources and biodiversity [21]. India has some of the highest levels of air pollution globally, with significant health impacts [22]. The over-extraction of groundwater and pollution from industrial and domestic sources has led to severe water crises. Urbanization, logging and agricultural expansion contribute to deforestation and soil erosion [23]. On the other hand, rapid industrialization and urbanization in China have led to severe air pollution, especially in major cities [24–27]. Besides air pollution, water pollution is another challenge; industrial-urbanization discharge, agricultural runoff and domestic sewage have heavily polluted China's water bodies. In addition, the heavy use of pesticides and industrial waste has led to significant soil pollution [28]. Similarly, South Africa is facing significant water scarcity issues due to climate change, overuse and pollution [29,30]. Furthermore, industrial activities, especially in mining and energy production, are contributing to air pollution. However, the most alarming threat to South Africa's rich biodiversity is habitat destruction and poaching, which require immediate attention and conservation efforts [31–34].

Although BRICS countries have been analyzed from various perspectives, little is known about the impact of energy production, innovation and the blue economy on environmental sustainability. Therefore, using the Driscoll standard error estimation, this study explores whether these factors enhance environmental sustainability or dim its impact in BRICS countries from 1990 to 2022. The study overcomes the issue of non-linear data analysis using panel quartile analysis for the causality interference of variables. The systematic literature review enabled the identification of the research gap. Section 3 presents the main variables and the data source. The authors present the study's results

in Section 4 and formulate conclusions showing future research avenues. Finally, we formulate a conclusion and point out opportunities for further research.

2. Literature Review

Sustainability includes advancing development without sacrificing the demands and livelihoods of future generations as well as current ones, all while safeguarding biological and human environments [35]. A key component for sustainable economic development is environmentally friendly energy intensity [36]. While high energy intensity can worsen environmental quality as it adds to the issue of climate change, less energy intensity may promote economic growth and environmental sustainability [37]. A decrease in energy intensity reduces the release of greenhouse gases and boosts energy availability, making it a worthwhile study topic in order to investigate the elements that influence energy intensity [38]. Regarding the nexus between energy intensity and environmental sustainability, empirical evidence indicates that BRICS heavily depend on fossil fuels for energy production, and, therefore, have a high energy intensity that harms the environment [39–41]. It is unavoidable that renewable energy will need to replace energy generated from fossil fuels, like oil, to address climate change and the energy crisis [42,43]. Using petroleum and coal has exacerbated the rise in global temperature and triggered a changing climate that has increased demand for renewable and environmentally conscious fuel substitutes [44,45]. Much advancement has been achieved regarding the industrial generation of renewable energy sources like biomass, sunlight and turbines that generate wind at low costs [46]. Technological advancements that enable the efficient and cost-effective use of renewable energy sources have led this accomplishment [47]. Additionally, hybrid renewable energy sources have been required [48].

In terms of empirical studies, a panel data study was conducted by [49] to examine the impact of green technology, economic complexity, renewable energy usage and human capital on the ecological footprint of the BRICS countries over the period 1990 to 2020. By using a cross-sectional autoregressive distributive lag (CS-ARDL) estimates technique, the results indicated that green technology, human capital and renewable energy protect the environment. However, economic complexity harms the ecosystem over time. The study also shows that different renewable energies interact with each other to safeguard the environment. Furthermore, green technology and renewable energy usage cooperate to protect the BRICS environment and act as like safeguard for biodiversity.

Since there are few technological solutions to address the shifts in the environment, which are amongst the greatest risks to the growth of modern technology, protecting intellectual property is essential. Nevertheless, patents seem to be a good choice to help speed up these processes and facilitate idea exchange. Advancements in green technologies can be used as instruments to manage the disparity between the economy and the planet future. Furthermore, there is an increase in the number of patents globally that pertain to technologies with low carbon footprints. Therefore, the optimal course of action for optimizing the probable appeal of environmental technology is to patent carbon capture methods. As the worldwide economy shifts to a sustainable one, patents are going to become more crucial in safeguarding and optimizing business advantages. Furthermore, intellectual property is going to be more important in building up environmentally friendly technologies that help to combat climate change if partnerships and cooperation are accepted by many countries and organizations [50]. According to [51], long-term pollution in the environment is caused by a lack of green energy. Green development, on the other hand, works to gradually lower pollution in the environment. Moreover, we discovered that short-term grants for technical cooperation can result in a decrease in environmental pollution. The existence of countless individuals is significantly impacted by technical

cooperation measures: measures to facilitate trade have significantly boosted business ownership; initiatives to conserve energy promote environmentally friendly economies and improve the quality of life among all citizens; and road pavement safety reviews contribute to increasing safer transportation networks for everyone, ultimately saving lives [52].

Regarding technological innovation and sustainability in BRICS countries, [53] empirically analyzed the nexus between carbon emission, natural gas and resources with environmental sustainability using panel data over the period 1990 to 2020. For empirical estimation, they used FMOLS and OLS along with canonical correlation regression and seemingly unrelated regression. Their results indicate that green technologies reduce carbon emission whereas natural resource extraction induces carbon emissions. Their findings indicated that natural gas production reduced carbon emissions in China and India. Furthermore, the estimations indicated that the unreciprocated extraction of natural resources contributed to a decrease in carbon emissions in Brazil and Russia, while simultaneously increasing carbon emissions in the other BRICS nations. Likewise, in another empirical study [54], using panel data from 1996 to 2021, they discovered that in BRICS countries, carbon emissions decreased in the presence of strong institutions through the control of corruption by investing and using more renewable energy resources. Their findings also highlighted that net foreign direct investment; urbanization and technological advancement appear to be harmful for the environment.

Approximately three billion individuals depend on the marine environment for their source of income, while 40% of the globe's populace lives close to the shore and oceans facilitate 80% of global trade [55]. Businesses around the world are being pushed to embrace environmentally friendly practices as the globe struggles with rising temperatures and the degradation of the environment. The maritime sector is not an exception, accounting for almost 90% of containerized trade worldwide. In actuality, the industry is essential to securing an environmentally friendly future because of its major environmental impact. The transport sector plays a significant role in the world's greenhouse gas emissions, which will likely increase in the coming years.

Implementing ecological concepts, contributing to the blue economy, managing fishing sustainably and using water-based assets can all contribute to economic growth, a secure food supply, better dietary habits and the lowering of poverty rates. Combined with fish farming, fishery supplies from inland and coastal areas provide food, nourishment and a significant source of livelihood for more than 820,000,000 individuals globally through collection, preparation, advertising and distribution. It is an important aspect of many seaside regions' conventional cultural heritage. The long-term sustainability of the world's fisheries supplies is threatened by factors including contamination, overfishing, illicit, unnoticed and unsupervised fishing and global warming [56].

In terms of blue economic impact on economic growth, ref. [57] analyzed the impact of China's blue economy on economic growth using time series data from 1980 to 2019. Fishing production from sea and agriculture fisheries along with trade and capital data were used as the control variables in analysis. By applying ARDL estimation techniques, their results indicate that the blue economy positively impacted economic growth in the long- and short-run in China. In a similar study for Bangladesh using time series data over the period 1990 to 2022 and by applying ARDL estimation, [58] showed that blue economy along with aqua-agricultural production positively enhanced economic growth, capital, and created an intensive labor supply. Using ARDL estimation, the results of [59] indicated that labor and marine trade are contributing factors of economic growth in KSA. Furthermore, negative shocks in energy intensity lead towards sustainable economic growth. The positive shocks in renewable energy, grants, marine trade and marine tourism are key factors for economic development. In another empirical research work for EU

countries, ref. [60] showed that maritime transport as a factor of blue economy positively increases economic growth.

Additionally, in terms of blue economy impact on environmental sustainability, [61] used panel data from 28 European countries over the period 2009 to 2018. By applying FMOLS and VECM estimation, their results indicate that the blue economy appears to harm the environment and thus causes greenhouse gas emissions. Furthermore, their results show that unidirectional causality influences the relationship between economic growth and greenhouse gas emissions in the long term. In terms of the short run, the casual effect has an influence on factors ranging from greenhouse gases to economic growth. In their research work, they used the gross added value of the global supply chain as a proxy for the blue economy.

Another empirical research work based on human activities showed that greenhouse gas (GHG) emissions, unsustainable economic growth and environmentally detrimental trading may threaten the blue economy (BE) [62]; the authors seeked to assess how GHG emissions, trade and economic growth affect the BE. A panel dataset of 25 Indian Ocean countries from 2002 to 2019 was used to do this. To estimate cointegration, we used the Westerlund error correction model. We used cross-sectional autoregressive distributed lag (CS-ARDL) to determine the variables' long-term association, which showed a significant long-term outcome but an inconsequential short-term outcome. The panel corrected standard error (PCSE) model was used to fix autocorrelation after this divergence. A two-step GMM test was then performed to assess robustness. This analysis found that trade hurts the BE, whereas GHG emissions and economic growth help. To meet the SDGs, all nations must include ocean-based solutions in their climate promises.

Although a large amount of research has been carried out regarding the relationship between energy production and environmental sustainability, there is still a lacuna regarding how innovation, the blue economy and energy intensity jointly affect environmental sustainability, especially with regards to the BRICS countries. While many studies exist on the topic, most of them focus on renewable energy or non-renewable energy intensity; however, do not fully take into consideration how fishing industries—the blue economy, ocean trade and technological cooperation—affect environmental sustainability in terms of carbon emissions for BRICS countries. Finally, the interaction between energy intensity, innovation and blue economy activities, with respect to environmental sustainability, has not been holistically investigated in BRICS economies, leaving a lacuna in understanding how these combined factors shape carbon emissions and resource efficiency. Given this fact, the research encompasses the concept of the blue economy in addressing fishing and ocean trade, adding technological cooperation among BRICS countries in order to show how cooperative ways of looking at marine sustainability and technology can help to progress toward a low-carbon world. This perspective brings novelty to the existing literature since the role of marine resources in environmental sustainability has often been undermined.

3. Research Framework, Data and Analytical Approach

Based on the research goals and the gap determined through the literature review, the formulated research question is as follows: How does ESG readiness moderate the relationship between energy use, innovation and environmental sustainability in the blue economy for BRICS countries? And the formulated research hypothesis is

H1. *The condition (to achieve environment sustainability) requires ESG readiness moderation in the presence of sustainable energy use, innovation and sustainable blue economy practice.*

Therefore, according to the research hypothesis, the research framework is presented in Figure 1 and indicates the complex interaction amongst energy use, innovation and the

blue economy with respect to environmental sustainability. Adding ESG readiness as a moderating factor indicates that policy and governance are crucial factors that shape up sustainable practices.

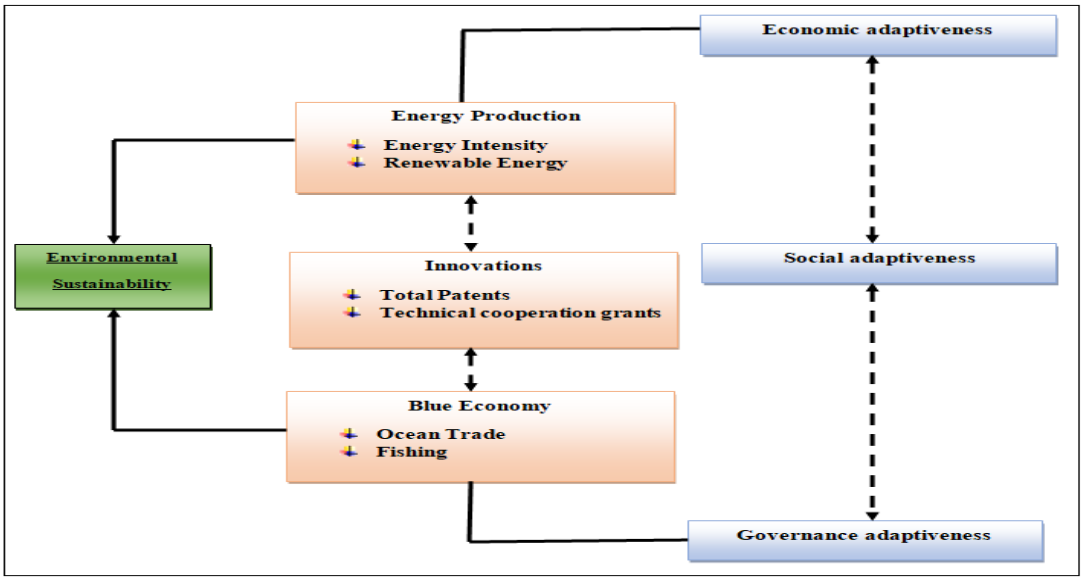


Figure 1. Research framework. Source: author.

3.1. Data

Environmental sustainability is proxied by CO_2 emissions (kt). Energy production is indicated by energy intensity as a level of primary energy (MJ/USD 2017 PPP GDP) along with renewable energy consumption (% of total final energy consumption). Similarly, innovation is indicated by resident and non-resident patent applications along with technical cooperation grants (BoP, currency USD). Furthermore, the blue economy consists of total fisheries production (metric tons) and total ocean trade (BoP, currency USD). The ESG readiness comprises index values extracted from the University of Notre Dame Global Adaptation Initiative—ND-GAIN Country Index.

In econometrics and statistics, missing values in a dataset promote biased estimation [63]. To mitigate the bias introduced by missing values, linear interpolation has been applied. Linear interpolation fills in missing values with estimations from the surrounding data points, using a given consistent trend among the points [64]. Mean imputation replaces the missing values with the average of the observed values for each variable, the advantage being that the general distribution remains and bias is minimized.

3.2. Analytical Approach

The analytical approach and estimation are based on the panel data methodology, which has several advantages as it helps to understand and estimate the longitudinal dynamics of environmental sustainability within BRICS countries. The panel data consist of multi-dimensional data involving measurements over time. Furthermore, each of the BRICS countries may present peculiarities that could affect environmental performance, given the different policy frameworks for industrial sectors and social factors. Panel data allow us to control for unobserved fixed-effects, isolating the impact of the variables of interest, energy intensity, the blue economy and technical innovation. Furthermore, by combining cross-sectional data (across the five countries in BRICS countries) with time dimension (across 22 years), panel data analysis increases the number of data points, enhancing the statistical power and precision of the estimated results. Therefore, it allows for more robust and accurate estimates of the relationship between variables.

$$\text{Log_CO}_2\text{it} = \alpha o + \alpha 1\text{Log_EIit} + \alpha 2\text{Log_REit} + \alpha 3\text{Log_TPit} + \alpha 4\text{Log_TCit} + \alpha 5\text{Log_TFit} + \alpha 6\text{Log_Tit} + \alpha 7\text{SOCit} + \alpha 8\text{ECOit} + \alpha 9\text{GOVit} + \text{uit} \quad (1)$$

In the above Equation (1), αo is the intercept, where α1 to α9 are the slopes; uit is the random error. Similarly, í is the cross-sections, and t indicates the time dimension from 1990 to 2022. Besides the ESG index, all other variables such as carbon emission (CO), energy intensity (EI), renewable energy consumption (RE), total patent (TP)—(patent applications, non-residents + patent applications, residents), technical cooperation grants (TC), total fisheries production (TF), ocean trade (T), and care are extracted from the World Bank database (WDI).

3.3. Summary Statistics and Correlation

The estimated descriptive statistics are presented in Table 1. The descriptive statistics consist of the mean and range statistics of panel data. Furthermore, the volatility in the variables is due to the significant difference in the range; thus, the standard deviation is also presented in Table 1. In addition, the skewness, kurtosis and Jarque–Bera results are presented in the table. Log_EI, Log_RE, Log_TC and GOC indicate negative skewness, whereas the rest of the variables are positively skewed. Lastly, the Jarque–Bera results indicate that the variables are not normally distributed.

Table 1. Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis	Jarque–Bera	Probability
Log_CO_2	165	13.881	1.118	12.196	16.213	0.425	2.222077	9.142303	0.010346
Log_EI	165	1.944	0.416	1.092	2.614	−0.25437	1.985827	8.850646	0.00197
Log_RE	165	2.845	0.972	1.157	3.969	−0.45006	1.75731	16.18718	0.000305
Log_TP	165	10.191	1.422	8.052	14.313	1.218373	4.436416	55.00703	0.000
Log_TC	165	19.585	1.008	9.903	20.828	−5.44623	52.88882	176.84	0.0000
Log_TF	165	15.190	1.603	12.989	18.273	0.435173	2.06933	11.1625	0.003768
Log_T	165	17.095	1.148	14.867	19.632	0.049847	2.304079	3.397934	0.002872
SCO	165	0.301	0.149	0.125	0.627	0.945319	2.524402	26.12987	0.000002
GOV	165	0.449	0.068	0.307	0.579	−0.01083	2.165942	4.785835	0.091363
ECO	165	0.482	0.146	0.170	0.856	0.951667	3.211984	25.21485	0.000003

Table 2 presents the correlation analysis among the variables. The results indicate that there is no multicollinearity among the used variables. Figure 2 presents the correlation analysis graphically.

Table 2. Correlation matrix.

Variables	Log_CO_2	Log_EI	Log_RE	Log_TP	Log_TC	Log_TF	Log_T	SCO	GOC	ECO
Log_CO_2	1									
Log_EI	0.387	1								
Log_RE	−0.265	−0.626	1							
Log_TP	0.808	0.062	−0.184	1						
Log_TC	0.433	0.125	−0.139	0.339	1					
Log_TF	0.819	0.295	−0.017	0.791	0.457	1				
Log_T	0.642	−0.281	0.055	0.826	0.309	0.616	1			
SCO	0.629	0.218	−0.641	0.669	0.427	0.472	0.5398	1		
GOV	−0.575	−0.291	0.433	−0.384	−0.325	−0.505	−0.275	−0.666	1	
ECO	0.418	0.180	−0.379	0.397	0.341	0.341	0.305	0.576	−0.479	1

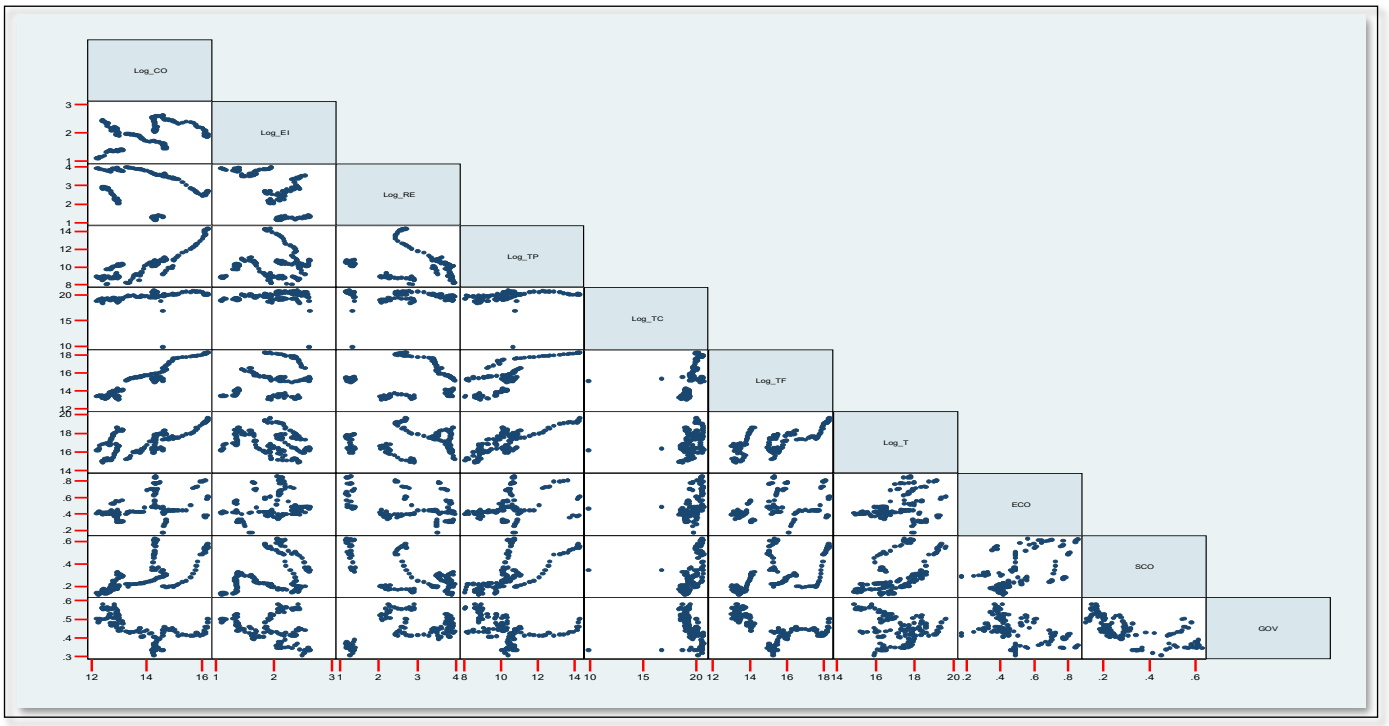


Figure 2. Matrix graph. Source: author.

4. Results

4.1. Panel OLS Estimation

Initially, panel regression estimation in this research work is conducted using a panel ordinary least squares estimation which is often applied to panel data analysis because of its simplicity, flexibility and foundational role. POLS give an easily interpretable estimate of the relations between the endogenous and exogenous variables. It assumes that the errors have a homoscedastic variance which is constant and the independent variables are uncorrelated with the error term. This makes OLS easy to apply and understand in the panel data context, though it may not catch all the complexities of the panel data. The OLS assumes the homoscedasticity of the error terms and no serial correlation. In panel data analysis, this is usually violated, which leads to inefficient and probably biased estimates. The results of POLS are presented in Table 3.

Table 3 reports the impact of energy production, innovation and the blue economy on environmental sustainability proxied by carbon emission for BRICS countries from 1990 to 2022 using POLS estimation. The study aims to obtain evidence of whether energy production, innovation and the blue economy enhance environmental sustainability or lessen its impact. Model 1 shows that, among six exogenous variables, renewable energy and total technical grant corporations positively reduce carbon emissions in BRICS countries. Thus, a one unit increase in renewable energy consumption and total technical cooperation grants tends to decrease carbon emission by 0.278% and 0.049%, respectively. Furthermore, the estimation results also reveal that a one unit increase in total patents, fishing industry and total ocean trade increases carbon emission by 0.083%, 0.598%, and 0.050%, respectively. By incorporating social readiness in the estimation according to model 2, the estimated results indicate the statistical significance and consistent signs of Log_RE, Log_TP, Log_TC, Log_TF and Log_T. However, the magnitude of the coefficients is slightly different. Similarly, the estimation results reveal that a one unit increase in social readiness decreases carbon emissions by 0.446%. By incorporating economic and governance readiness in models 3 and 4, the estimated results indicate the statistical significance and consistent

signs of all variables similar to models 1 and 2. However, the magnitude of the coefficient is not slightly different. The economic and governance readiness indicates an insignificant association with carbon emission and is thus statistically insignificant. According to model 5, the estimation results indicate that a one unit increase in social readiness improves environmental sustainability by 0.490%. On the other hand, renewable energy and technical cooperation enhance environmental sustainability by reducing carbon emissions; thus, a one unit increase in renewable energy and total technical cooperation decreases carbon emissions by 0.332% and 0.038%, respectively. The estimation outcomes indicate that a one unit increase in total patents along with the fishing industry and ocean trade increases carbon emission by 0.097%, 0.604% and 0.058%, respectively. However, economic and governance readiness appears to be insignificant in the model.

Table 3. POLS estimation (endogenous variable: carbon emission).

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
Log_EI	0.010 (0.048)	0.080 (0.052)	0.019 (0.048)	0.020 (0.054)	0.061 (0.054)
Log_RE	−0.278 (0.017) ***	−0.338 (0.026) ***	−0.285 (0.018) ***	−0.283 (0.023) ***	−0.332 (0.027) ***
Log_TP	0.083 (0.018) ***	0.088 (0.017) ***	0.083 (0.018) ***	0.080 (0.020) ***	0.097 (0.020) ***
Log_TC	−0.049 (0.011) ***	−0.044 (0.010) ***	−0.047 (0.013) ***	−0.048 (0.011) ***	−0.038 (0.012) ***
Log_TF	0.598 (0.015) ***	0.614 (0.016) ***	0.601 (0.015) ***	0.603 (0.020) ***	0.604 (0.019) ***
Log_T	0.050 (0.018) **	0.057 (0.017) ***	0.051 (0.018) ***	0.053 (0.018) ***	0.058 (0.019) ***
SOC	-	−0.446 (0.147) ***	-	-	−0.490 (0.164) ***
ECO	-		−0.095 (0.077)	-	−0.056 (0.078)
GOV	-		-	0.079 (0.214)	−0.238 (0.231)
R^2	0.602	0.684	0.557	0.687	0.708
Adjusted-R^2	0.595	0.678	0.570	0.677	0.699

*** Indicate level of significance at 1% and ** indicates the level of significance at 5%.

4.2. Driscoll and Kraay Standard Errors

This method appears appropriate in panel data analysis in the existence of autocorrelation, heteroskedasticity and cross-sectional dependence in standard errors. In addition, the main advantages of Driscoll–Kraay's [65] standard errors against other estimators are their robustness to heteroskedasticity and autocorrelation. Furthermore, dependencies between cross-sections may exist in many empirical applications, especially studies between countries or regions, such as the BRICS countries. For example, trade or environmental policies or energy technologies can have an impact on many countries at the same time, therefore leading to cross-sectional dependence. Driscoll and Kraay's [65] method is particularly suitable for large-T, small-N datasets; thus, it is highly suitable for this BRICS countries analysis (i.e., T-33 and N-5). It is worth noting that the time dimension is larger than the cross-sectional dimension. Table 4 estimates Driscoll and Kraay's standard errors.

Table 4. Fixed-effect Driscoll-Karaay Estimation (endogenous variable: carbon emission).

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
Log_EI	0.314 (0.058) ***	0.024 (0.056) ***	0.313 (0.065) ***	0.303 (0.063) ***	0.248 (0.064) ***
Log_RE	−0.475 (0.024) ***	−0.439 (0.031) ***	−0.476 (0.027) ***	−0.467 (0.027) ***	−0.445 (0.036) ***
Log_TP	0.147 (0.012) ***	0.085 (0.014) ***	0.157 (0.011) ***	0.148 (0.012) ***	0.191 (0.014) ***
Log_TC	−0.352 (0.005) ***	−0.024 (0.003) ***	−0.030 (0.004) ***	−0.035 (0.005) ***	−0.021 (0.003) ***
Log_TF	0.269 (0.037) ***	0.238 (0.044) ***	0.236 (0.037) ***	0.271 (0.037) ***	0.211 (0.044) ***
Log_T	0.138 (0.020) ***	0.161 (0.025) ***	0.143 (0.019) ***	0.136 (0.020) ***	0.165 (0.024) ***
SOC	-	−0.608 (0.201) ***	-	-	−0.568 (0.222) ***
ECO	-	-	−0.183 (0.048) ***	-	−0.159 (0.044) ***
GOV	-	-		−0.130 (0.138)	0.045 (0.188)
No of Observation	165				
No of groups	5				

*** Indicate level of significance at 1%.

Table 4 reports the impact of energy production, innovation and blue economy on environmental sustainability proxied by carbon emission for BRICS countries over 1990–2022 using fixed-effect Driscoll standard error estimation. The estimated results explore whether energy production, innovation and blue economy enhance environmental sustainability or lessen its impact. Model 1 shows that, among six exogenous variables, renewable energy positively reduces carbon emissions in BRICS sample countries. Thus, a one unit increase in renewable energy consumption and total technical cooperation grants tends to decrease carbon emission by 0.475% and 0.352%, respectively.

Furthermore, the estimation results also reveal that a one unit increase in energy intensity, total patents, fishing industry and total ocean trade increases carbon emission by 0.314%, 0.147%, 0.269% and 0.138%, respectively. By incorporating social readiness in the estimation according to model 2, the estimated results indicate the statistical significance and consistent signs of Log_EI, Log_RE, Log_TP, Log_TC, Log_TF and Log_T; however, the magnitudes of coefficients are slightly different. Similarly, the estimation results reveal that a one unit increase in social readiness decreases carbon emissions by 0.608%, respectively. By incorporating economic and governance readiness in models 3 and 4, the estimated results indicate the statistical significance and consistent signs of all variables similar to models 1 and 2. However, the magnitude of the coefficients is slightly different. Economic readiness indicates a negative and significant association with carbon emissions; thus, a one unit increase in economic readiness decreases carbon emissions by 0.183% respectively. However, the governance readiness coefficient appears hostile but statistically insignificant. According to model 5, the estimation results indicate that a one unit increase in social and economic readiness improves environmental sustainability by 0.568% and 0.159%, respectively. On the other hand, renewable energy and technical cooperation enhance environmental sustainability by reducing carbon emission; thus, a one unit increase in renewable energy and total technical cooperation decreases carbon emission by 0.445% and 0.021%, respectively. The estimation outcomes also indicate that one unit increase in

energy intensity, total patents, fishing industry, and ocean trade increase carbon emission by 0.248%, 0.191%, 0.211% and 0.165%, respectively.

4.3. Panel Quantile Regression (QR)

The first quantile regression (QR) studies are based on Roger Koenker and Gilbert Bassett [66,67]. The early QR method offers convenience for estimating conditional quantiles and is flexible. Interest in the QR method has increased in econometrics and statistics in the following periods [68]. In addition, panel data and QR techniques have continued to develop in parallel for many years. However, the QR method was not used in panel data analysis until Konker [69,70]. The method has become popular because the panel data technique allows the analysis of individual-specific heterogeneity and process fit dynamics. It is also argued that traditional OLS models are inadequate for empirical analysis. Horowitz and Markotu [50] mentioned the shortcomings and problems of OLS models. Thus, the PQR method started to attract much attention due to applying the QR method to panel data and its ability to analyze individual effects [68]. Studies on the PQR method have increased over time in the literature [69,70].

The QR method has many advantages over classical dynamic panel data. For example, the QR model is less sensitive to outliers. Since most of the variables used in panel analyses have a heterogeneous structure, the QR method gives better results in heterogeneous panels. In addition, panel data fixed-effects estimators give biased results in the presence of lagged dependent variables. The instrumental variable quantile regression method is recommended Galvao [68]. The QR method is robust and essential to model heterogeneous effects and explain unobserved heterogeneity [71]. At the same time, the fixed-effects PQ (FE-PQR) method provides more flexible estimations than the classical fixed-effects and random effects methods because it controls for individual-specific heterogeneity. The results of the FE-PQR model are accessible from the deviations that occur in classical least squares (OLS) methods when the time dimension is small. Therefore, the FE-PQR method was applied in this study due to its advantages. The QR method conveniently reveals the asymmetrical properties of variable distributions. This method calculates the coefficients across different quantiles.

If Y_i is the dependent variable and X_i is the explanatory variable in the QR model, the formula of the conditional quantiles functions of Y is as follows:

$$QY_i\left(\tau \middle| X_i = X_i^T \beta_\tau\right) \tag{2}$$

Although the QR method gives solid results, it ignores the country's unobserved heterogeneity. Therefore, instead of the traditional QR method, refs. [66,67] have studied techniques that apply quantile regressions for panel data. Based on the studies of Chen and Lei [72], the FE-PQR method, which allows for unobserved individual heterogeneity, was used to examine the effects of SOV, GOV, ECO, GDP and TOU on EF in this paper.

$$QY_{it}\left(\tau_k \middle| \alpha i,\ X_{it} = \alpha_i + X_{it}^T \beta(\tau_k),\ i = 1, \ldots, N;\ t = 1, \ldots, T\right) \tag{3}$$

In Equation (2), the i represents the relevant individual. t is the indicator of time. N gives the number of observations on i. T is the number of observations at time t. τ is the sample quantile with values between 0 and 1. Y_i is the target-dependent variable. X_i^T is the vector of the independent variables. αi has a displacement effect on the conditional quantiles of the response. Here, the impact of X_{it}^T covariates depends on the relevant t quantiles.

The unobserved fixed-effect can be estimated with the covariate effects for different levels of quantiles. Accordingly, the model for parameter estimation is set up as follows:

$$\min_{(\alpha,\beta)} \sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{i=1}^{N} \left(W_{k\rho\tau k} \left(yit - \alpha i - X_{it}^{T} \beta\tau_k \right) \right) + \lambda \sum_{i}^{N} |\alpha i|,\ i = 1, \ldots, N;\ t = 1, \ldots, T \quad (4)$$

In model 3, the term K is an indicator of quantiles. X_{it} is a matrix of the dependent variable. $\rho_{\tau k}$ is a term denoting the quantile loss function. Finally, W_k is a relative weight given for the kth quantile. W_k represents the contribution of the kth quantile in the fixed-effect estimation.

$$QFE_{it}\ (\tau \mid \alpha_i, Y_t, X_{it} = \alpha_i + Y_t + \beta_{1\tau}X + \beta_{2\tau}X2 + \beta_{3\tau}X3 + \beta_{4\tau}X4 + \beta_{5\tau}X5) \quad (5)$$

Similarly, based on FE-PQR, Table 5 indicates the nexus between environmental sustainability, innovation, energy intensity and ocean trade under the shadow of social readiness. According to the FE-PQR analysis results, the outcomes indicate that the energy intensity coefficient positively and significantly affects the carbon emission on high quantiles (Q60 and Q80), which are 0.176 and 0.199, respectively. Furthermore, the results indicate that total trade and fishing positively increase carbon emissions across all the quantiles. However, the lowest effect of total patent on carbon emission can be observed at a high quantile; thus, Q80 appears to be 0.044. On the other hand, the most substantial effect of total fishing was observed in Q80, which was 0.654. Similarly, the coefficient of renewable energy usage indicates a negative association across all the quantiles; however, this effect varies. As per the outcomes, the most substantial impact of renewable energy is at the 80th quantile, which is 0.407, whereas the lowest is at Q20, at 0.277. On the other hand, the estimation results indicate that social readiness suggests a negative association with carbon emissions at Q60 and Q80; thus, the coefficient appears to be 0.763 (most vital and significant) and 0.703 (weak and important).

Table 5. Panel quantile regression—social readiness.

Variable	Q20	Q40	Q60	Q80
Log_EI	0.060 (0.032)	0.038 (0.093)	0.176 (0.097) **	0.199 (0.090) **
Log_RE	−0.277 (0.043) ***	−0.301 (0.040) ***	−0.388 (0.030) ***	−0.407 (0.039) ***
Log_TP	0.136 (0.024) ***	0.108 (0.026) ***	0.078 (0.030) **	0.044 (0.028) ***
Log_TC	−0.041 (0.028)	−0.038 (0.028)	−0.039 (0.022)	−0.027 (0.018)
Log_TF	0.564 (0.024) ***	0.610 (0.033) ***	0.647 (0.026) ***	0.654 (0.022) ***
Log_T	0.058 (0.033)	0.035 (0.027)	0.052 (0.033)	0.073 (0.031)
SOC	−0.242 (0.288)	−0.331 (0.229)	−0.763 (0.269) ***	−0.703 (0.265) ***
Constant	4.395353 (0.545) ***	4.631407 (0.7412094)	4.850 (0.760) ***	4.629988 (0.547)

*** Indicate level of significance at 1% and ** indicates the level of significance at 5%.

Likewise, Table 6 indicates the nexus between environmental sustainability, innovation, energy intensity and ocean trade. According to the results of the FE-PQR analysis, the outcomes suggest that energy intensity, total cooperation grants and economic readiness are insignificant across all the quantiles. Furthermore, the coefficient of renewable energy usage indicates a negative association across all the quantiles; however, this effect varies. As per the outcomes, the most substantial impact of renewable energy is at the 80th quantile, 0.343, whereas the lowest is at Q20, 0.224. On the other hand, the estimation results indicate that Log_TP appears to increase carbon emission at a low quantile; thus, Q20 has a coefficient of

0.144 and Q40 has 0.108. Similarly, the result shows that Log_TF positively increases carbon emission across all the quantiles; therefore, from Q20 to Q60, it indicates an increased trend—0.565 to 0.635—whereas at Q80, it falls to 0.614. Lastly, Log_T indicates a positive and significant association with carbon emission; at Q60, it is 0.053, and at Q80, it appears to be 0.089.

Table 6. Panel quantile regression (economic readiness).

Variable	Q20	Q40	Q60	Q80
Log_EI	0.088 (0.095)	0.007 (0.110)	−0.099 (0.111)	−0.028 (0.074)
Log_RE	−0.224 (0.030) ***	−0.258 (0.044) ***	−0.321 (0.052) ***	−0.343 (0.037) ***
Log_TP	0.144 (0.028) ***	0.108 (0.035) ***	0.044 (0.045)	0.031 (0.039)
Log_TC	−0.043 (0.037)	−0.040 (0.068)	−0.051 (0.057)	−0.036 (0.046)
Log_TF	0.565 (0.024) ***	0.596 (0.037) ***	0.635 (0.039) ***	0.614 (0.040) ***
Log_T	0.025 (0.027)	0.027 (0.018)	0.053 (0.029) **	0.089 (0.027) ***
ECO	−0.113 (0.200)	−0.003 (0.147)	−0.039 (0.184)	−0.050 (0.136)
Constant	4.55721 (0.5772733)	4.718191 (1.131919)	4.992551 (0.920) ***	4.481124 (0.7758067)

*** Indicate level of significance at 1% and ** indicates the level of significance at 5%.

Table 7 indicates the nexus between environmental sustainability, innovation, energy intensity and ocean trade. According to FE-PQR analysis results, the outcomes suggest that Log_EI, Log_TC and governance readiness are insignificant across all the quantiles. Furthermore, the coefficient of renewable energy usage indicates a negative association across all the quantiles; however, this effect varies. As per the outcomes, the most substantial impact of renewable energy is at the 80th quantile, which is 0.400, whereas the lowest is at Q20, 0.263. On the other hand, the estimation results indicate that Log_TP appear to increase carbon emission at low quantiles, and thus Q20 has a coefficient of 0.148 and Q40 has a coefficient of 0.125. Similarly, the result shows that Log_TF positively increases carbon emission across all the quantiles; therefore, from Q20 to Q80, there is an increased trend—0.562 to 0.661. Lastly, Log_T indicates a positive and significant association with carbon emission; at Q80, it appears to be 0.083.

Table 8 indicates the impact of energy production, innovation and the blue economy on environmental sustainability under ESG readiness; the graphical presentation of quantiles is presented in Figures 3–12. According to the FE-PQR analysis results, the outcomes indicate the impacts of Log_EI, Log_TC, economic governance and the blue economy on environmental sustainability under ESG readiness. The graphical presentation of the quantiles indicates that readiness is insignificant across all the quantiles. Furthermore, the coefficient of renewable energy usage indicates a negative association across all the quantiles; however, this effect varies. As per the outcomes, the most substantial effect of renewable energy is at the 80th quantile, which is 0.400, whereas the lowest is at Q20, 0.263. On the other hand, the estimation results indicate that Log_TP appears to increase carbon emission across all the quantiles; however, this effect varies. At the low quantile Q20, with a coefficient of 0.147, which seems to be a high value, there is an increase in carbon emissions across all the quantiles; thus, from Q20 to Q80, the coefficient is 0.067. Similarly, the result indicates that Log_TF positively increases carbon emissions across all the quantiles; thus, from Q20 to Q80, there is the indication of an increased trend—0.558 to

0.641. Lastly, Log_T indicates a positive and significant association with carbon emissions; at Q60 and Q80, it appears as 0.052 and 0.073, respectively. Lastly, the coefficient of social readiness seems essential and negatively associated with carbon emissions at Q60 and Q80, respectively; thus, the co-efficient values are 0.680 and 0.090, and are most robust at Q60 and weak at Q80.

Table 7. Panel quantile regression (governance readiness).

Variable	Q20	Q40	Q60	Q80
Log_EI	0.074 (0.035)	0.045 (0.104)	0.100 (0.096)	0.051 (0.084)
Log_RE	−0.229 (0.025) ***	−0.232 (0.046) ***	−0.327 (0.043) ***	−0.334 (0.040) ***
Log_TP	0.148 (0.022) ***	0.125 (0.042) ***	0.039 (0.033)	0.018 (0.038)
Log_TC	−0.038 (0.035)	−0.038 (0.041)	−0.053 (0.068)	−0.043 (0.040)
Log_TF	0.562 (0.020) ***	0.580 (0.036) ***	0.642 (0.036) ***	0.661 (0.036) ***
Log_T	0.013 (0.024)	0.026 (0.033)	0.057 (0.041)	0.083 (0.039) **
GOV	−0.264 (0.313)	−0.214 (0.303)	−0.090 (0.267)	−0.163 (0.289)
Constant	4.892 (0.664) ***	4.706 (0.923) ***	4.898 (1.328)	4.616 (0.816)

*** Indicate level of significance at 1% and ** indicates the level of significance at 5%.

Table 8. Panel quantile regression ESG readiness.

Variable	Q20	Q40	Q60	Q80
Log_EI	0.070 (0.063)	0.003 (0.096)	−0.129 (0.094)	−0.153 (0.098)
Log_RE	−0.263 (0.055) ***	−0.260 (0.053) ***	−0.367 (0.037) ***	−0.400 (0.044) ***
Log_TP	0.147 (0.034) ***	0.131 (0.030) ***	0.095 (0.034) ***	0.067 (0.038) *
Log_TC	−0.041 (0.038)	−0.035 (0.054)	−0.025 (0.043)	−0.018 (0.031)
Log_TF	0.558 (0.041) ***	0.584 (0.041) ***	0.622 (0.027) ***	0.640 (0.021) ***
Log_T	0.048 (0.037)	0.029 (0.025)	0.052 (0.024) **	0.073 (0.028) **
SOC	−0.274 (0.289)	−0.285 (0.260)	−0.680 (0.345) **	−0.090 (0.355) **
ECO	0.112 (0.089)	0.034 (0.093)	−0.074 (0.156)	−0.108 (0.136)
GOV	−0.106 (0.245)	−0.352 (0.281)	−0.372 (0.282)	−0.451 (0.277)
Constant	4.465 (0.787) ***	4.783 (0.889)	4.793 (0.867) ***	4.636 (0.621)

*** Indicate level of significance at 1%; ** indicates the level of significance at 5% and * indicates the level of significance at 10%.

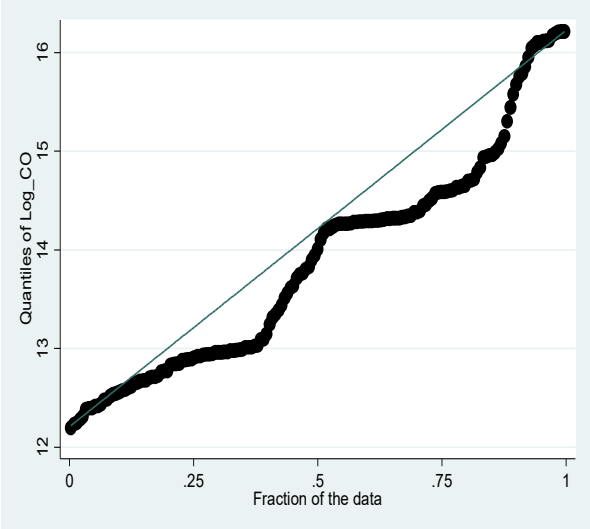


Figure 3. Quantile of Log_CO.

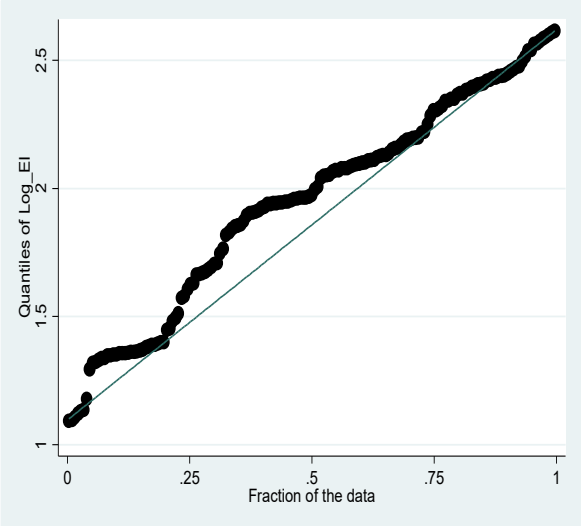


Figure 4. Quantile of Log_EI.

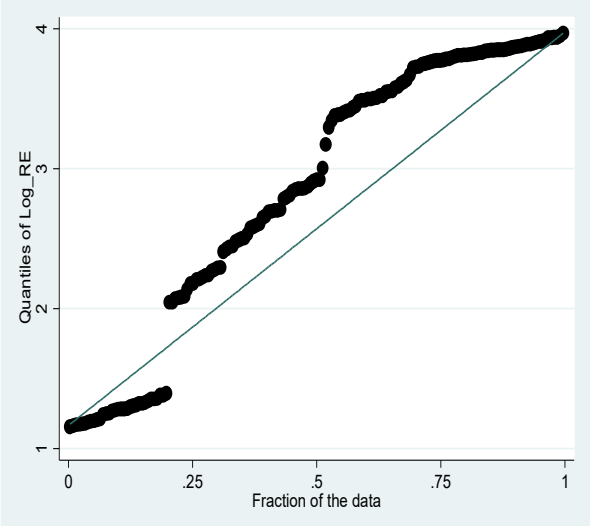


Figure 5. Quantile of Log_RE.

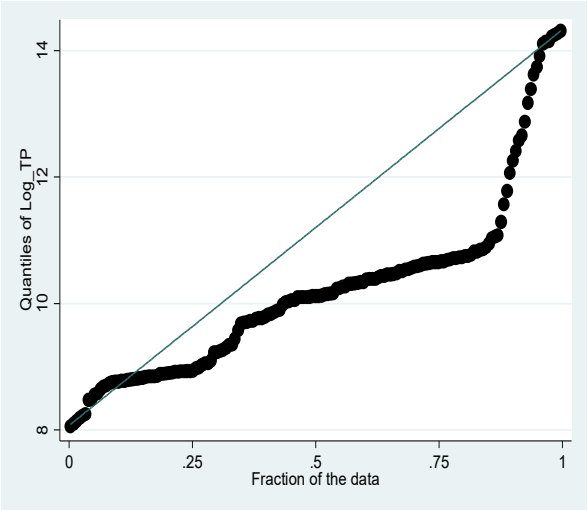


Figure 6. Quantile of Log_TP.

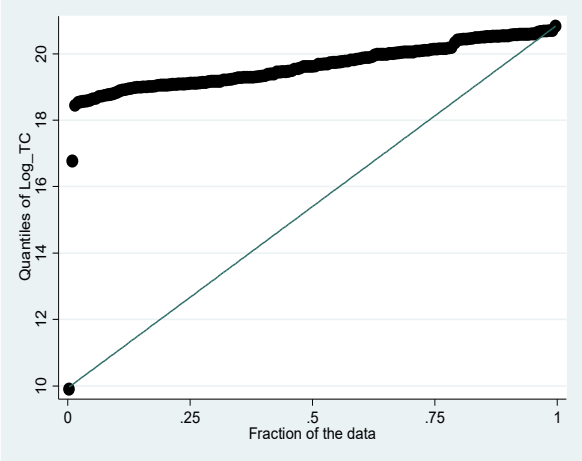


Figure 7. Quantile of Log_TC.

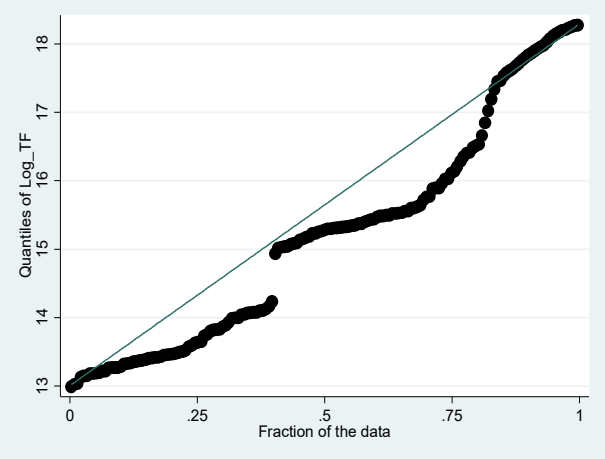


Figure 8. Quantile of Log_TF.

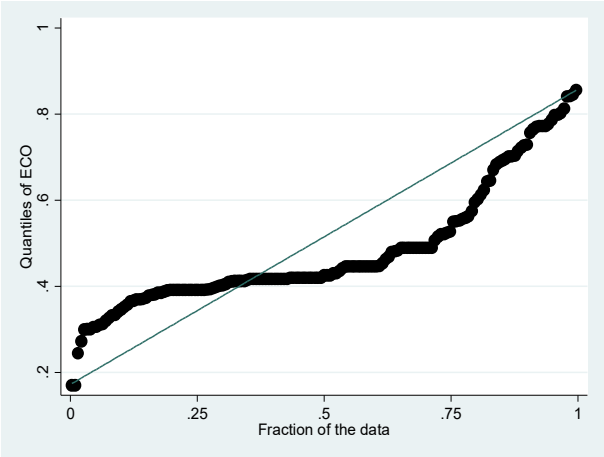


Figure 9. Quantile of ECO.

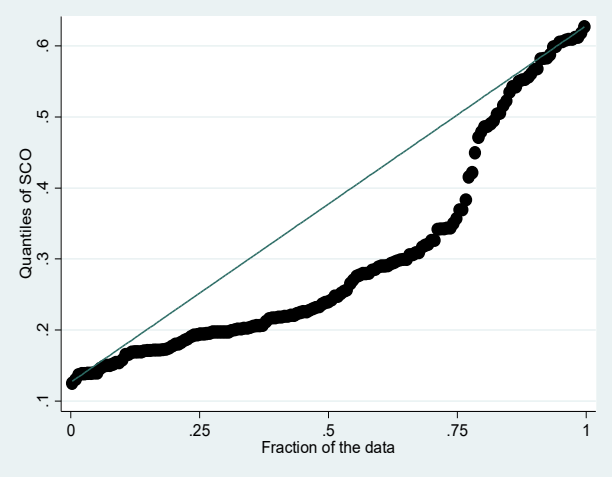


Figure 10. Quantile of SCO.

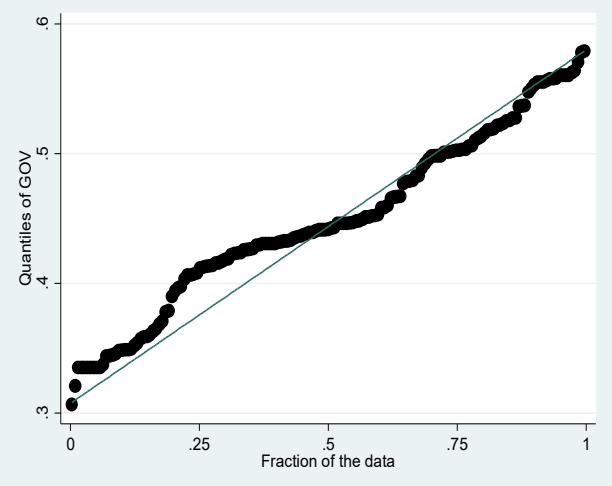


Figure 11. Quantile of GOV.

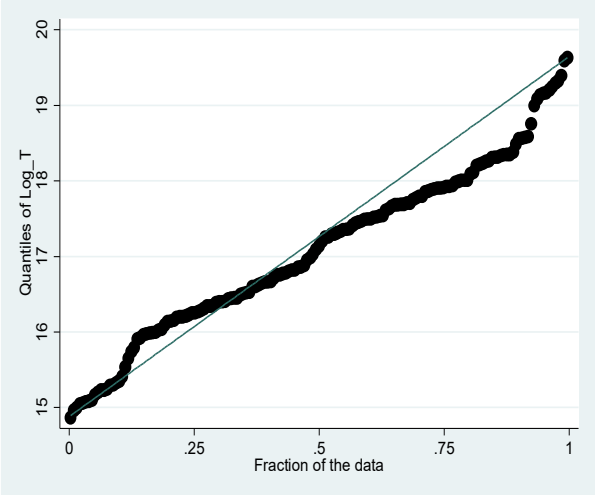


Figure 12. Quantile of Log_T.

5. Discussions

This paper analyzes the nexus between energy intensity, innovation mechanisms and the blue economy on environmental sustainability from 1990 to 2022 for BRIC countries. The Driscoll and Kraay [65] robust standard errors-type approach, which accounts for heteroskedasticity, autocorrelation and cross-sectional dependence, is used in this study for empirical analysis and panel quantile regression as a robust estimation.

We must consider the fact that many BRICS countries have instituted policies to spur the development and integration of renewable energy, including subsidies, feed-in tariffs and renewable energy targets. Accordingly, renewable energy reduces carbon emissions in BRICS countries by providing clean, zero-emission energy, improving energy efficiency, reducing dependence on coal, enabling distributed energy generation and benefiting from technological innovations. Since these countries remain committed to integrating more renewables into their energy grids, further carbon emission reductions are bound to be recorded; consequently, they will contribute toward the mitigation of global climate change [73]. Furthermore, the negative relationship between renewable energy and carbon emissions has been shown by other research [74–77].

The outcome indicates that technological advances do not appear to have improved environmental sustainability in BRICS regions—this is due to the fact that the technology used in BRICS countries fosters the economic growth process. The technology is heavily based on resource intensive mechanisms and thus prioritizes economic growth over sustainability [77]. Likewise, the results indicate that to achieve environmental sustainability BRICS countries must enhance their technological cooperation and governance via the pathway to green cooperation in accordance with the Paris agreement [78]. In the BRICS group, the national economies still heavily depend on coal-powered technology to raise production and generate economic growth. As such, they must shift to renewable energy. The integration of more technologically advanced energy infrastructure will go a long way in enabling them to effectively reduce carbon intensity in generating electricity. There are a considerable number of renewable energy technologies that, especially regarding wind and solar, have higher energy conversion efficiencies than traditional fossil fuels. It means that renewable technologies generate more energy per unit of input used, reducing the carbon footprint from electricity generation in general.

The findings also reveal that BRICS countries' economies are heavily based on trade and the overexploitation of marine resources, which has a negative impact on the sustainability in BRICS countries [79,80]. The blue economy, ocean trade and fishing industries

are very vital for the economy, but due to numerous environmental reasons, they cause damage to sustainability efforts in BRICS nations. As a result of overfishing in BRICS nations—mostly China and India—many key fish stocks have been depleted, disrupting marine ecosystems. Intensive methods of fishing, such as bottom trawling and illegal, unreported and unregulated fishing, are among those contributing to the depletion of species, the loss of biodiversity and habitat destruction. Overfishing depletes marine food resources, taking out the predators at the top of the food chain and thus lowering marine biodiversity. Fishing and shipping are significant industries in BRICS nations that also contribute to the overall amount of carbon emitted through human activity. Vessels used for fishing require fossil fuels to operate, as do cargo ships, releasing carbon dioxide and other pollutants into the atmosphere. A lot of carbon footprint comes out from fishing and shipping, which in many ways contributes to global warming. Furthermore, it also fuels further climate change, with serious impacts on ocean temperatures, marine biodiversity and rising sea levels. The acidification and warming of the ocean by pollution emanating from the blue economy—in particular, shipping—is spreading and destroying sensitive ecosystems like coral reefs and fish stocks dependent on undisturbed oceanic conditions. The ability of marine organisms to form calcium carbonate shells has been reduced due to ocean acidification, which has restricted the diversity of marine life and destroyed sources of food.

The direct association between the blue economy and carbon emissions has also been shown by previous researchers [62]. Research has also suggested that in BRICS countries, economic readiness plays a crucial role in decreasing carbon emissions by fostering a transition to low-carbon practices and technologies. Numerous other studies such as [81,82] also highlight this close relationship, indicating that economic readiness decreases carbon emissions. Lastly, the findings confirm that social awareness appears to be crucial aspect for enhancing environmental sustainability in BRICS countries. This is due to the fact that the government emphasis on green practices and the adoption of sustainable lifestyles leads to a reduction in carbon emissions. Furthermore, BRICS governments also provide support for low-carbon technologies by increasing public participation in climate initiatives. These findings are also shown by relevant studies [83].

6. Conclusions

This paper provides an in-depth analysis of the complex inter-relationships of energy intensity and technological advancement using the concept of the blue economy within the ESG readiness framework for the BRICS countries. The results provide a significant understanding of environmental sustainability dynamics when the positive and negative impacts of different factors are considered. The results also fulfill the research gap on how the interaction of energy intensity, technological advancement and blue economy factors are in line with varying levels of ESG readiness within the emerging BRICS economies context. The findings indicated that increasing renewable energy use significantly improves environmental sustainability. Renewable energy sources like solar and wind curtail the demand for fossil fuels, which, as of now, are the primary cause of greenhouse gas emissions among BRICS countries. High energy intensity means that there is a high amount of energy use per unit of economic output and, hence, this exerts a negative influence on environmental sustainability due to high fossil fuel consumption.

Contrarily, while technological innovation can often characterize a positive influence on the environment, the evidence found in this research reveals the fact that in BRICS countries, technology utilization exerts a negative influence, particularly in areas not adhering to environmental laws. In the absence of sufficient environmental policy and governance on technological expansion, unsustainable practices may be utilized, such as increased

industrial pollution which causes environmental degradation. This paper establishes that although the blue economy has potential for economic growth and sustainability, the way the blue economy is managed in the BRICS countries tends to contribute to environmental degradation. Certain contributors to environmental degradation include overfishing, marine pollution and unsustainable ocean trade practices. Without more stringent regulation and sustainable use, this part of the economy will also continue to be a source of ecological stress in these regions. This paper, therefore, underlines the aspect of ESG readiness in regulating such effects. Indeed, countries that have been able to integrate ESG principles into governance frameworks have, in one way or another, managed to use energy and technology for sustainability. On the other hand, ESG readiness still differs across the BRICS countries, which again results in various environmental impacts regarding the use of technology or the so-called blue economy.

In terms of policy recommendation, consequently, the BRICS nations should build a collaborative renewable energy network for sharing the best practices, technologies and innovations in solar energy, wind energy and bioenergy. Such initiatives may include common R&D programs in the improvement of renewable energy technologies across borders. The establishment of a BRICS technology exchange program, intended for knowledge transfer and collaborative innovation in renewable energy technologies, should be considered. Such cooperation could tap into the respective technical strengths of the BRICS countries. They should also establish joint research and innovation centers on renewable energy, financed by BRICS, for stimulating cooperation on actually developing clean energy technologies. Furthermore, BRICS countries should focus on sustainable fishing quotas and seasonal bans to make sure overfishing is avoided in order to ensure the sustainability of fish populations for the long term. They should also invest in advanced technologies and real-time data tracking systems like satellite monitoring and AI-based systems for tracking fishing activities, enforcing regulations and detecting IUU fishing in the BRICS countries.

Furthermore, regional cooperation should be strengthened among the BRICS countries to construct a common framework that tries to solve trans-boundary issues related to ocean trade, pollution and the overexploitation of marine resources. BRICS countries should also encourage efforts for ESG considerations in all blue economy-related investment and business practices. Companies related to both fishing and maritime industries should report on the state of the environment to their respective governments, and should be informed about guidelines on sustainability.

The authors are aware of the limitations of the research; these include the indicators used, the period chosen for the analysis, the group of countries subject to the research and the method used. For this reason, as a future research direction, the authors consider focusing the research on another group of countries such as ASEAN, given the challenges that Asian economies face in the context of the transition to a low-carbon economy. In addition, future research should consider the impact of digitalization and the use of new technologies such as blockchain on the green transition.

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